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MANNED EVALUATION OF A DIVER HEATER FOR SDV APPLICATIONS USING HYDROGEN CATALYTIC REACTIONS

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NAVAL SEA SYSTEMS COMMAND
Navy Experimental Diving Unit

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A series of thirty total man dives up to six hours in duration was conducted in 35 to 40 °F water to assess the thermal protective efficacy of an experimental hydrogen catalytic heating system. Mean dive duration increased 145% (from 91.2 to 223 min) when diver-subjects were connected to the catalytic heater rather than dressed in similar diver dress without heating. The prototype heater significantly enhanced the thermal protection of the fingers and toes, body regions where thermal stress had been a primary reason for aborting dives. The prototype heater also improved thermal protection of other skin regions (chest, thigh, calf, and upper arm). In-water and postdive surveys confirmed the overall thermal benefits of the prototype hydrogen catalytic heater.

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INTRODUCTION

Naval Sea Systems Command (NAVSEA) 00C tasked Navy Experimental Diving Unit (NEDU) to assess the effectiveness of an experimental diver heater being developed in partnership by Duke University and NSWC Panama City under sponsorship of the Office of Naval Research.[1] This proof of concept study was designed to investigate whether a prototype hydrogen catalytic heater, when used in conjunction with a recently developed integrated closed-circuit tube suit–dry suit thermal protection garment, was capable of satisfying the thermal protection needs of up to six combat swimmers in long-duration cold water missions.

In FY00 under Office of Naval Research (ONR) funding, a concept assessment was conducted to determine the feasibility of using a hydrogen catalytic heating system with closed-circuit hot water suits in a swimmer delivery vehicle (SDV) application shown in Figure 1. Analysis indicated that up to 2 kilowatts (kW) of heat could be produced, sufficient heat to sustain up to six divers in 32 °F (0 °C) water, with only 25 standard ft^3 of hydrogen per hour. Analysis further indicated that these heating levels could be achieved by flowing only 1% hydrogen in air mixtures (substantially below the minimum combustible level of 4% hydrogen) through the catalyst bed at a pressure of 100 pounds per square inch (psi). A laboratory prototype heater using hydrogen catalytic reactions in a semiclosed circuit, a heater described in Appendix A and shown conceptually in Figure 1, was built and tested in the Hydrospace Laboratory at the Coastal Systems Station in Panama City, FL, during July 2000. These tests confirmed that 1% hydrogen in 100 psi air is adequate to produce more than 2 kW of heat (sufficient heat for six divers), and that the heater could deliver up to 4.5 gallons per minute (gal/min) water flow rate at 100–102 °F (37.8–38.9 °C).

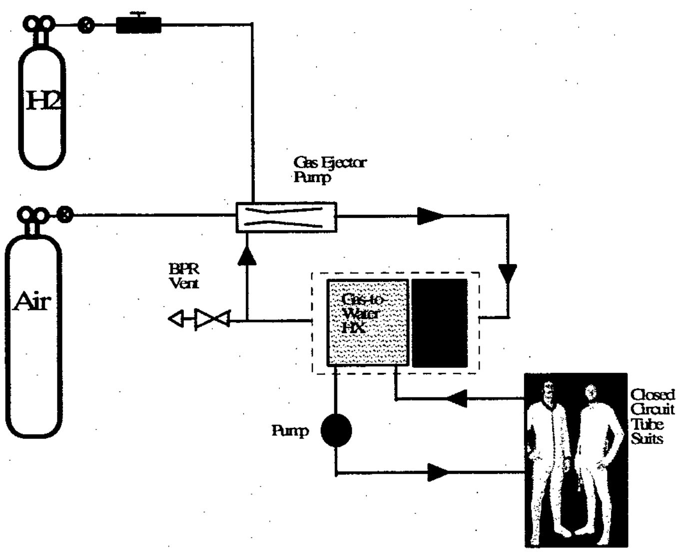
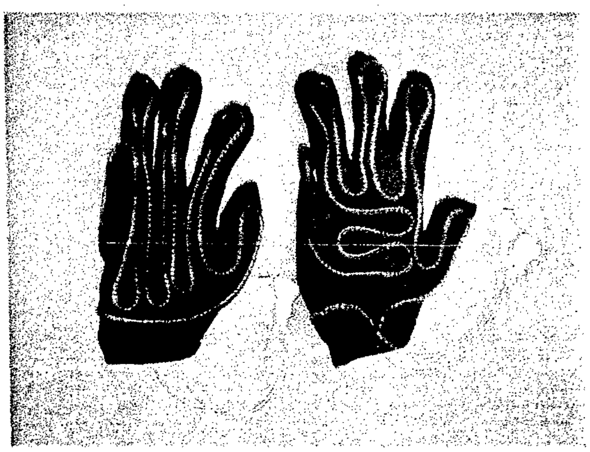
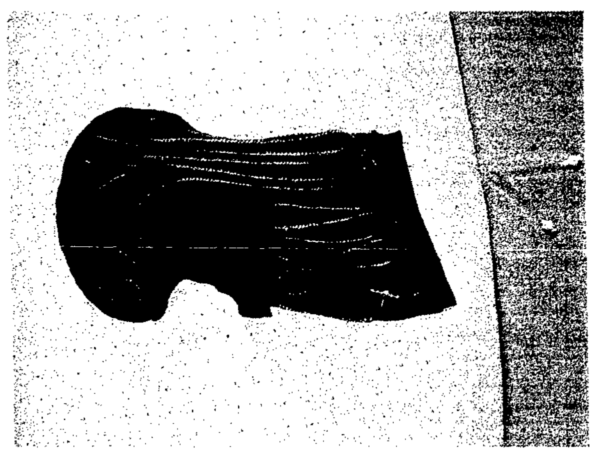


Figure 1: Concept sketch of hydrogen catalytic combustion water heater for SDV applications.

In the latter half of FY02 NEDU transitioned the unmanned laboratory testing into manned testing.[2] This proof of concept dive study was designed to verify the results of unmanned testing in simulated combat swimmer missions and verify that the prototype hydrogen catalytic heater was capable of satisfying the thermal protection needs of up to six combat swimmers in long duration cold water missions. Results from this testing confirmed that the hydrogen catalytic heater was fully capable of providing adequate levels of supplemental heating for six divers in 35 °F water. However, results further indicated that a redesign of the commercial tube suits used with the heater was deemed necessary to provide thermal comfort to the divers' hands and feet and to prevent a thermal short through the diver's head. With an average duration of 127 minutes recorded during this previous test series (n = 18), nearly half aborted due to cold hands and feet or due to excessive drop in core temperature.

Subsequently, Med-Eng, Inc. of Toronto, Canada, was contracted to fabricate closed-circuit heating gloves and hoods, shown in Figure 2, to be integrated with the existing tube suits. A single length of small diameter tubing (I.D. of 0.098 inches, O.D. of 0.178) was stitched to each nylon stretch glove and hood. Quick-disconnect (QD) fittings were attached to the tubing supply and return ends to connect each component to the existing tube suit. This tubing size was found to give a water flow rate of approximately 150 mL/min for e





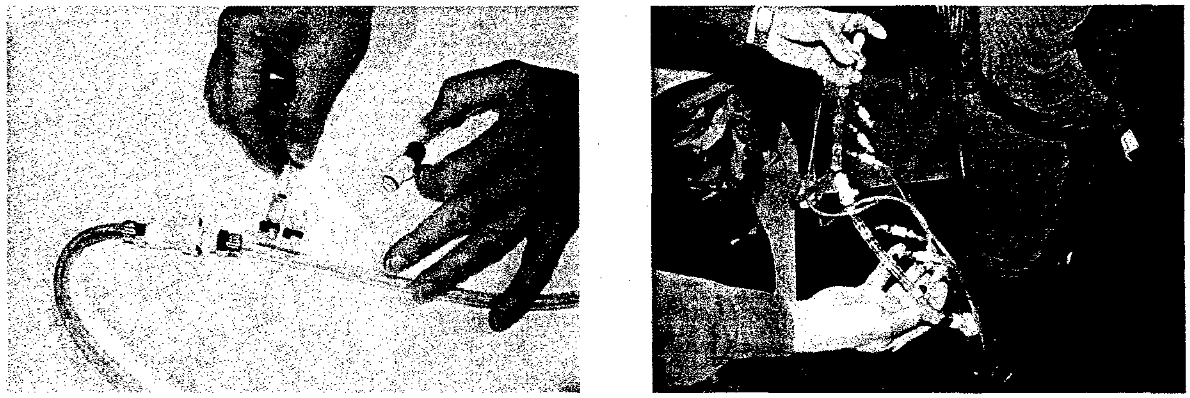


Figure 3. T-connectors (left) were added to the existing tube suit circuit on the supply and return sides to integrate the heated gloves and hood. The circuit manifold (right) is shown connected to the existing closed-circuit tube suit.

The objective of this present evaluation was to repeat the catalytic heater evaluations conducted in FY02 with diver-subjects wearing the recently developed integrated closed-circuit tube suit–dry suit thermal protection garment.

METHODS

GENERAL

During January-February 2005 NEDU conducted a series of five test dives up to six hours in duration to compare the thermal status of diver-subjects connected to the prototype hydrogen catalytic heating system with the status of divers wearing a commercial dry suit. During each test dive six diver-subjects connected to and disconnected from the heater circuit at a prescribed schedule to simulate diver lock-in and lockout from an SDV. Statistical data comparing psychological and physical thermal status from the prototype heater with those from the NEDU Protocol 04-44/32160 evaluation of the identical commercial dry suit with Thinsulate liner (but without heating) as a baseline configuration determined the thermal benefit of the prototype heater.[3] Six test subjects in the current study had participated as subjects in the baseline study during the previous week. All tests were conducted to simulate long-duration cold water conditions in the NEDU test pool, where water temperature was maintained between 1.7 and 4.4 °C (35 and 40 °F). Divers remained immobile while either lying or sitting in chairs on the bottom of the test pool, and they subjectively reported their thermal comfort at 30-minute intervals during each dive.

DIVER-SUBJECTS

Nine U.S. Navy male divers — whose ages, weights, and body fat statistics are listed in Table 1 — volunteered to participate in the study. Skinfold measurements from three locations (chest, abdomen, and thigh) were used to estimate the body density for each diver-subject using the generalized equation from Jackson and Pollock,[4]

$$Body\ Density = 1.10938 - 0.0008267 * sum + 0.0000016 * sum^2 - 0.0002574 * age ,$$

and the Siri equation[5] was used to convert these body densities into estimates of the percentage of body fat as

$$\% Fat = \left[\frac{4.570}{Body\ Density} - 4.142 \right] * 100\% .$$

These equations are documented to provide good estimates for white males between the ages of 20 and 80.

To ensure that their baseline core temperatures were not elevated before their dives, diver-subjects did not conduct physical training (PT) on dive days.

The protocol[6] was reviewed and approved by the NEDU Institutional Review Board (IRB). All test subjects reviewed the protocol and voluntarily consented to participate in the study.

Table 1.
Age, Weight, and Body Fat Characteristics of Diver-Subjects.

Diver ID	Age	Weight (kg)	Weight (lb)	Body fat%
1	35	88.0	194.0	16.8
2	40	85.3	188.0	11.2
3	30	88.4	195.0	11.0
4	36	92.5	204.0	18.5
5	49	91.8	202.5	16.9
6	40	80.7	178.0	12.9
7	40	72.6	160.0	8.4
8	24	95.2	210.0	9.0
9	42	98.0	216.0	15.6
Mean	37.3	88.1	194.2	13.4
Std Dev	7.2	7.8	17.2	3.7
Min	24	72.6	160.0	8.4
Max	49	98.0	216.0	18.5

DIVER DRESS AND BREATHING APPARATUS

For hygiene purposes, diver-subjects wore external catheter urine collection systems during the dive. Diver dress (Figure 4) consisted of four layers. The first layer was Capilene lightweight underwear and socks. The second layer was the closed-circuit

tube suit with integrated gloves and hood consisting of multiple tube circuits woven into a thin stretch fabric. The third and fourth layers included a commercial M400 Thinsulate thermal undergarment with a bootie, hood, and gloves liner and a DUI TLS350 dry suit with an attached hood, all procured from Diving Unlimited International (DUI), Inc. All divers wore three-finger dry glove shells. During the last three test dives half of the dive subjects wore experimental aerogel booties and glove liners in place of the commercial Thinsulate booties and glove liners to investigate any advantages of combining passive insulation improvements to the divers' garments with active heating from the prototype heater. The aerogel components had been shown to have superior insulation when they were compared to Thinsulate in a previous thermal study.[7]

Diver-subjects used the U.S. Navy MK 20 underwater breathing apparatus (UBA) with built-in communications. A complete diver dress and breathing apparatus configuration is shown in Figure 5.

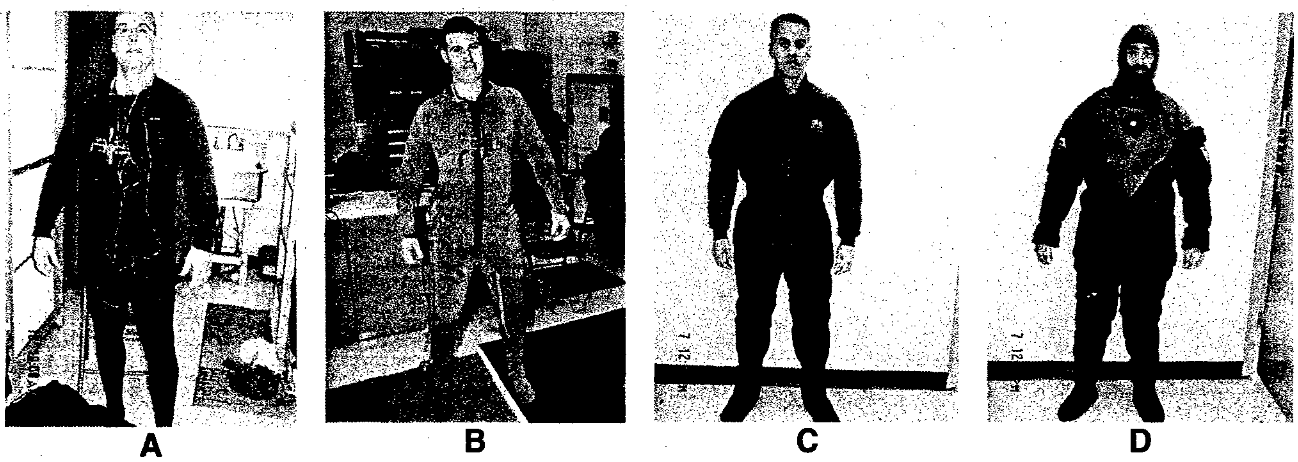


Figure 4. Layers of diver dress from left to right: **(A)** the Capilene lightweight underwear and socks; **(B)** the closed-circuit tube suit; **(C)** the M400 Thinsulate thermal undergarment; and **(D)** the TLS350 dry suit with an attached hood (three-finger dry gloves not shown). A DTTR worn around the neck is shown in (A) and (B).

INSTRUMENTATION

A YSI series 700 (Yellow Springs Instruments, Inc; Yellow Springs, OH) indicator of core and surface temperatures was used to monitor rectal (T_{rec}), finger (T_{finger}), and toe (T_{toe}) temperatures in real time and also to monitor physiological safety. Depth, time, and temperature recorders (DTTR; PAG Automasjon A/S, Mo i Rana, Norway) were used to record chest, thigh, calf, and upper arm skin temperatures for postdive thermal assessment of these areas. Their sampling rates and data storage capacities are adequate for recording skin temperature changes through a six-hour dive.

Figure 5. Diver wearing the TLS350 dry suit with three-finger, "lobster claw" gloves as he prepares to enter the test pool.

PROCEDURES

The prototype heater was evaluated during a series of five test dives, with up to six divers connected to the heating circuit during each dive. To control carryover thermal debt from a previous dive, no diver could initiate a second dive for at least 40 hours.

Baseline core temperatures were recorded immediately before diver-subjects were dressed. While the divers were dressing, the heater technicians initiated the heater, and circuit water temperatures were allowed to stabilize at 105 °F. Core, toe, and finger temperature signals were verified before the diver-subjects entered the water. After the dive supervisor cleared diver-subjects, dive time was initiated as each diver entered the water and traveled to the bottom of the test pool in pairs. Upon reaching the bottom, each diver connected with QDs to the prototype heater circuit and positioned himself in a seated or lying position to simulate a long-duration SDV transit. Core, toe, and finger temperatures were logged at the start of the dive and every minute thereafter until the divers exited the water. Diver-subjects were continually monitored for the duration of the dive (six hours) or until termination criteria were met. A standby diver was available at all times while diver-subjects were in the water, and a hot tub and warm fluids were available to them after diving.

During each test dive some or all of the test subjects disconnected from the heater circuit to simulate a lockout from an SDV according to the test phases shown in Table 2. Each test phase was completed after the indicated number of divers either disconnected or reconnected to the heater circuit and the heater circuit water temperatures were seen to stabilize, as determined by the principal investigator (PI).

Table 2.
Test Phases.

Test Phase	Divers on Heater Circuit	Event
1	0	6 divers are on the surface until the heater water circuit stabilizes.
2	6	Divers enter the test pool, two at a time; connect into the heater circuit; and remain until the heater water circuit temperatures stabilize.
3	2	4 excursion divers disconnect from the heating circuit until the heater water circuit temperatures stabilize.
4	6	4 excursion divers reconnect to the heating circuit and remain until the water circuit temperatures stabilize.
5	4	2 excursion divers disconnect from the heating circuit until the heater water circuit temperatures stabilize.
6	6	2 excursion divers reconnect to the heating circuit and remain until the water circuit temperatures stabilize.
7	0	All 6 divers disconnect from the heating circuit until the heater water circuit temperatures stabilize.
8	6	All 6 excursion divers reconnect to the heating circuit and remain for the remaining test duration.

To subjectively assess diver thermal status, a thermal assessment questionnaire (Appendix B) was administered to the divers via the MK 20 communication system approximately every thirty minutes throughout dives. A postdive questionnaire (Appendix C) was used to collect general usability data.

TERMINATION CRITERIA

The tests were terminated before the six-hour duration if any of the following events occurred:

- A diver's core temperature was ≥1.5 °C (2.7 °F) below his baseline for at least five minutes or became ≤35.0 °C (95.0 °F) at any time.
- A toe or finger temperature was ≤12.0 °C (53.6 °F) for at least five minutes or became ≤10.0 °C (50.0 °F) at any time.
- A toe or finger temperature exceeded 40.6 °C (105 °F) for at least five minutes.
- A diver requested that a test be terminated.
- A dive watch officer, diving supervisor, diving medical officer, or diving corpsman determined that a dive was unsafe to continue.
- The Principal Investigator determined that termination was appropriate.

If a single skin temperature sensor failed, diver comfort determined whether a test was terminated. (The frequency with which the in-water questionnaire was administered was increased to every 15 minutes for that diver.)

RESULTS

GENERAL

The results are reported in six subsections: dive duration; real-time finger, toe, and core temperature data; DTTR data; subjective questionnaire data; postdive interviews; and

heater performance data. Statistical analyses are limited to data from diver subjects who were not connected to an adjunct heating system[7] and from test dives in which the entire heating system (including tube suit and supply lines) functioned properly. Analytical comparisons assuming unequal variances at 30-minute intervals were conducted to parallel the administration of in-water questionnaires. The number of comparisons was determined by the shortest dive (63 min) in previously recorded dives without heating.[7] The alpha level was set at .05 for all inferential tests.

No dive was aborted due to hydrogen heater operation. However, other failures in the heating system resulted in dive aborts: tubesuit flooding ($n = 5$) and complications in supply line flow ($n = 4$). Four dives were aborted for reasons unrelated to diver thermal status: a faulty rectal probe ($n = 1$) and a full urine bag ($n = 3$). No dives were aborted because of medical considerations.

DIVE DURATION

Complete dive duration data and abort criteria are provided in Table 3 and illustrated in Figure 6. Mean dive duration was longer after tube suit and supply modifications (Test Days 3–5: 264 min) than it was in early dives (Test Days 1–2: 188 min) without these design improvements; however, the probability of observing this difference by chance exceeded the alpha criterion: $t(12) = 1.73$, $p > .05$. Therefore, all heated dives with the same diver dress configuration were pooled for the analytical comparisons.

Table 3.
Dive Durations (Minutes) and Abort Criteria over the Five Test Days.

	Test Day									
	1		2		3		4		5	
Diver ID	Duration	Abort Criterion	Duration	Abort Criterion	Duration	Abort Criterion	Duration	Abort Criterion	Duration	Abort Criterion
1	123	finger			275[a]	urine bag full	240	head/feet[V]	243[a]	flooded suit[V]
2	149	toe	11	tubesuit failure	103	core/flow	245	toe	360[a]	max duration
3	27	faulty rectal			312[a]	urine bag full	360	max duration	360[a]	max duration
4	52	No heat/finger	254	finger	230	toe	360[a]	max duration	140	finger/flood Larm
5	285	jaw pain[V]								
6	157	finger/toe	360	max duration	232	urine bag full	127[a]	finger/flow	360	max duration
7			88	jaw pain[V]						
8			77	flooded suit	94	core/flow			183	tight neckseal[V]
9			90	feet[V]			27[a]	flooded suit		

Notes. [V]Diver-subject voluntarily aborted dive.
[a]Thinsulate glove and boot liners were replaced with aerogel liners.

The thermal protection afforded by the hydrogen heater system (H2) resulted in longer dive durations than baseline thermal protection (No Heat): $t(16) = 5.31$, $p < .05$. When

the Thinsulate glove and boot liners were replaced with aerogel liners to supplement the thermal protection afforded by the hydrogen heater system (H2a), mean dive durations were longer than they were when the diver wore the Thinsulate liners (H2): $t(17) = 2.99$, $p < .05$.

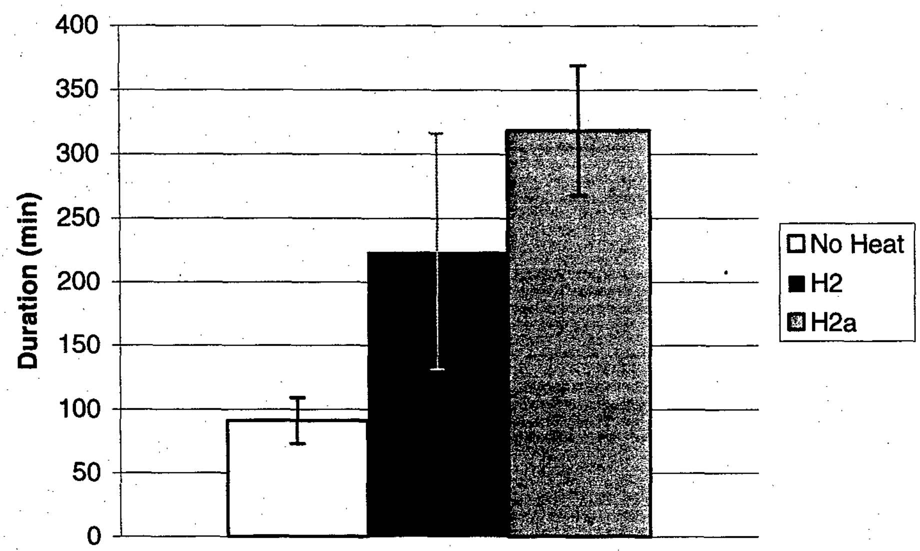


Figure 6. Mean dive durations (min) for unheated dives (No Heat) and heated dives without supply hose and/or tube suit complications: Thinsulate body suit and liners (H2); aerogel glove and boot liners (H2a). Error bars represent one standard deviation.

FINGER, TOE, AND CORE TEMPERATURES

Temperature drops from baselines were calculated up to the 63-minute mark of each dive in order to assess the thermal protection afforded by the prototype heater. Finger, toe, and core temperature changes from baselines at the 30- and 60-minute dive intervals are presented in Table 4 and illustrated in Figures 7 and 8.

Temperature drops in the finger and toe at the 30-minute dive interval were attenuated more when divers were connected to the hydrogen heating system (H2) than when they were in comparable diver dress without an adjunct heating system (NoHeat): $t(18) = 4.59$, $p < .05$ (finger), and $t(19) = 4.81$, $p < .05$ (toe). This pattern of thermal protection was also evident at the 60-minute interval: $t(19) = 5.87$, $p = < .05$ (finger), and $t(19) = 5.23$, $p < .05$ (toe). Core temperature did not vary as a function of thermal protection.

Temperature drops in the finger at the 30- and 60-minute heated dive intervals were attenuated more when divers wore aerogel glove liners (H2a) than when divers wore Thinsulate glove liners (H2): $t(16) = 2.39$, $p < .05$ (30-minute), and $t(12) = 2.55$, $p < .05$ (60-minute). Temperature drops in the toe did not vary as a function of boot liner.

Table 4.
Mean Finger, Toe, and Core Temperature (°C) Changes from Baseline with and without Heating.

	30 Minutes			60 Minutes		
	No Heat	**H2**	**H2a**	**No Heat**	**H2**	**H2a**
	(*n* = 6)	**(*n* = 15)**	**(*n* = 6)**	**(*n* = 6)**	**(*n* = 15)**	**(*n* = 6)**
Finger	−13.59	−4.46	−1.69	−18.18	−3.69	−3.53
	1.53	−5.57	3.30	1.74	−7.61	4.08
Toe	−7.47	−2.48	−3.45	−10.63	−3.93	−5.23
	1.44	3.40	2.04	1.67	4.19	3.24
Core	0.47	0.48		0.17	0.24	
	0.30	0.32		0.39	0.33	

Note: Mean temperature changes (top) from predive baselines are reported with one standard deviation (below): diver dress configuration without heat (No Heat), diver dress configuration with heat (H2), and diver dress configuration with aerogel glove and boot liners and heat (H2a).

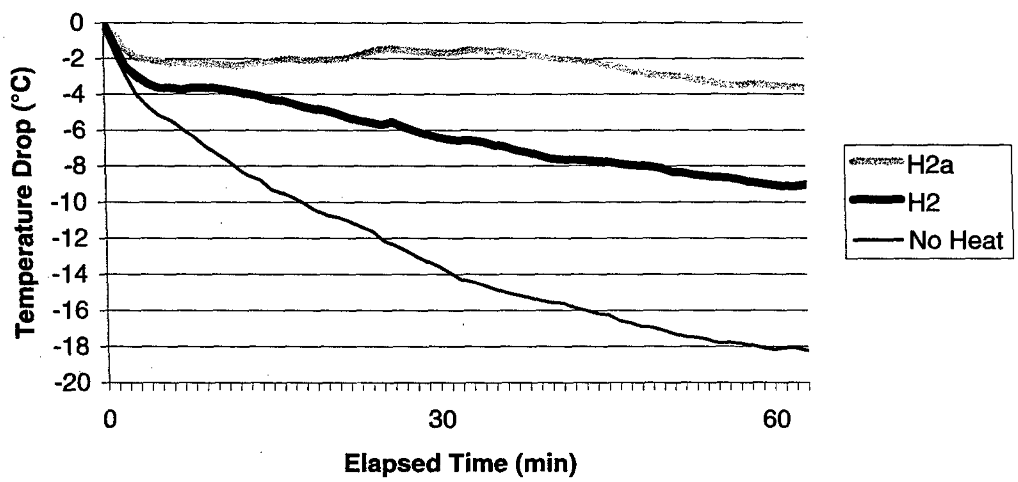


Figure 7. Mean finger temperature (°C) drop profiles without supply hose and/or tube suit complications: aerogel glove and boot liners (H2a); Thinsulate glove and boot liners (H2); and unheated dives (No Heat). Data are shown up to the shortest (63 min) recorded unheated dive.

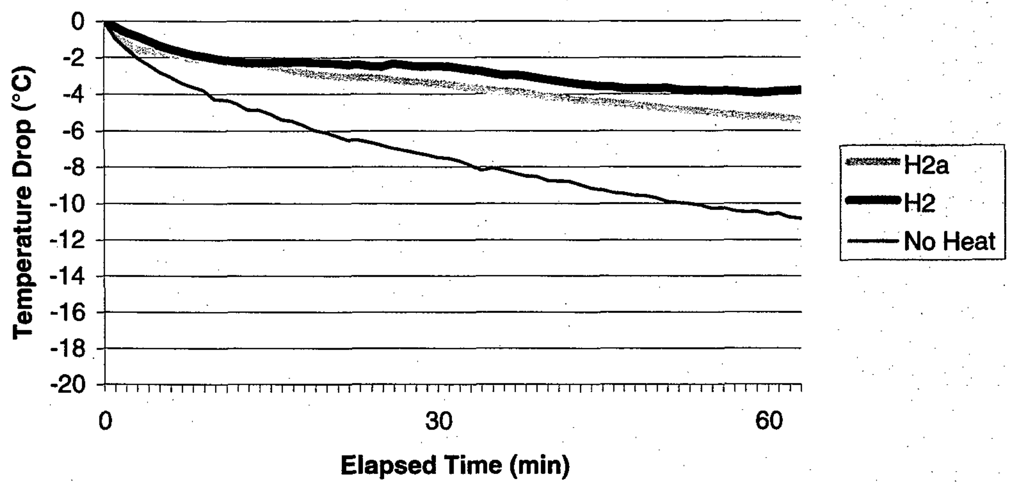


Figure 8. Mean heated toe temperature (°C) drop profiles without supply hose and/or tube suit complications: Thinsulate glove and boot liners (H2); aerogel glove and boot liners (H2a), and unheated dives (No Heat). Data are shown up to the shortest (63 min) recorded unheated dive.

DEPTH, TIME, AND TEMPERATURE RECORDINGS

Global Skin Temperatures

Because of the difficulty in measuring skin temperatures of many anatomical sites, the formula developed by Ramanathan[8] was used to calculate the mean body temperature and heat storage for measurements of depth, time, and temperature. The mean skin temperature values were based on regional weighting according to the percentage of body surface area. The formula for mean skin temperature (T_{sk}) is

$$T_{sk} = 0.3 \cdot (chest + upper\ arm\ temperatures) + 0.2 \cdot (thigh + calf\ temperatures).$$

Mean skin temperature drops from baseline at the 30- and 60-minute intervals are presented in Table 5 and illustrated in Figure 9.

Table 5.
Mean DTTR Skin Temperature (°C) Drops from Baseline with and without Heating.

	30 Minutes		60 Minutes	
	No Heat (n = 6)	H2 (n = 15)	No Heat (n = 6)	H2 (n = 15)
Mean	–5.50	–1.01	–7.38	–1.92
Std Dev	1.95	1.38	1.70	1.79

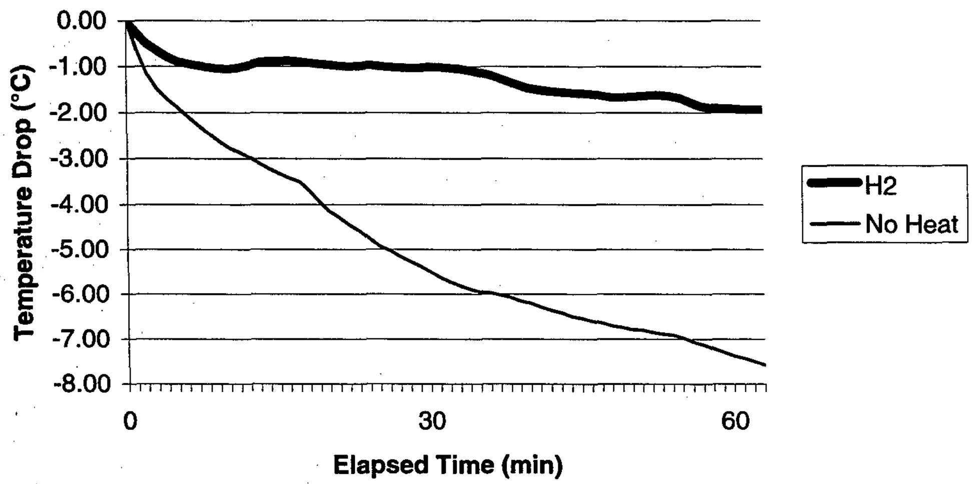


Figure 9. Mean skin temperature (°C) drop from predive baselines with (H2) and without (No Heat) heating. Data are shown up to the shortest (63 min) recorded baseline dive without heating.

Mean skin temperature drops at the 30- and 60-minute dive intervals were attenuated more when divers were connected to the hydrogen heating system (H2) than when they were in comparable diver dress without an adjunct heating system (No Heat): $t(7) = 5.24$, $p < .05$ (30-minute), and $t(9) = 6.38$, $p < .05$ (60-minute).

Localized Skin Temperatures

For chest, thigh, calf, and upper arm at the 30- and 60-minute dive intervals, mean skin temperature drops from baseline are presented in Table 6. Figures 10–13 illustrate these skin temperature drops from baseline with and without heating.

Table 6.
Localized Mean DTTR Skin Temperature (°C) Drops from Baseline with and without Heating.

	30 Minutes		60 Minutes	
	No Heat	H2	No Heat	H2
Chest	–4.86 2.64	–0.46 1.68	–6.54 2.93	–1.08 2.12
Thigh	–6.99 2.51	–1.03 2.49	–9.33 2.09	–1.88 2.75
Calf	–5.94 3.24	–1.79 1.79	–8.29 4.19	–3.32 2.48
Upper Arm	–3.91 1.82	–1.06 1.22	–5.13 1.78	–1.86 1.52

Note: Mean temperature drops (top) are reported with one standard deviation (below). Diver #4 was excluded from No Heat calf calculations, since DTTR data for this location were lost.

Chest, thigh, calf, and upper arm temperature drops at the 30-minute dive interval were attenuated more when divers were connected to the hydrogen heating system (H2) than when they were in comparable diver dress without an adjunct heating system (No Heat): $t(7) = 3.47$, $p < .05$ (chest); $t(7) = 5.52$, $p < .05$ (thigh); $t(6) = 3.03$, $p < .05$ (calf); and $t(7) = 3.55$, $p < .05$ (arm). This pattern for thermal protection was also evident at the 60-minute interval: $t(8) = 3.81$, p = < .05 (chest); $t(10) = 7.32$, p = < .05 (thigh); $t(6) = 2.52$, $p < .05$ (calf); and $t(8) = 5.14$, $p < .05$ (arm).

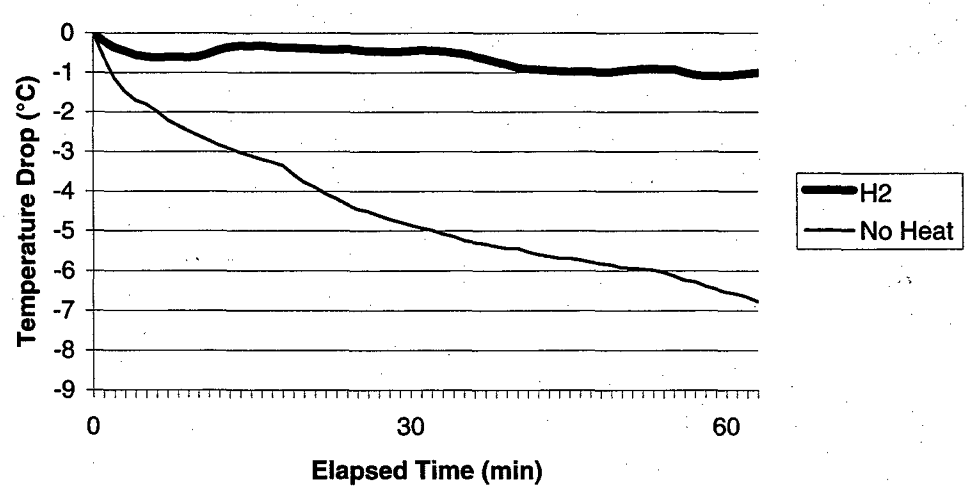


Figure 10. Mean chest skin temperature (°C) drops from predive baselines with (H2) and without (No Heat) heating. Data is shown up to 63 min.

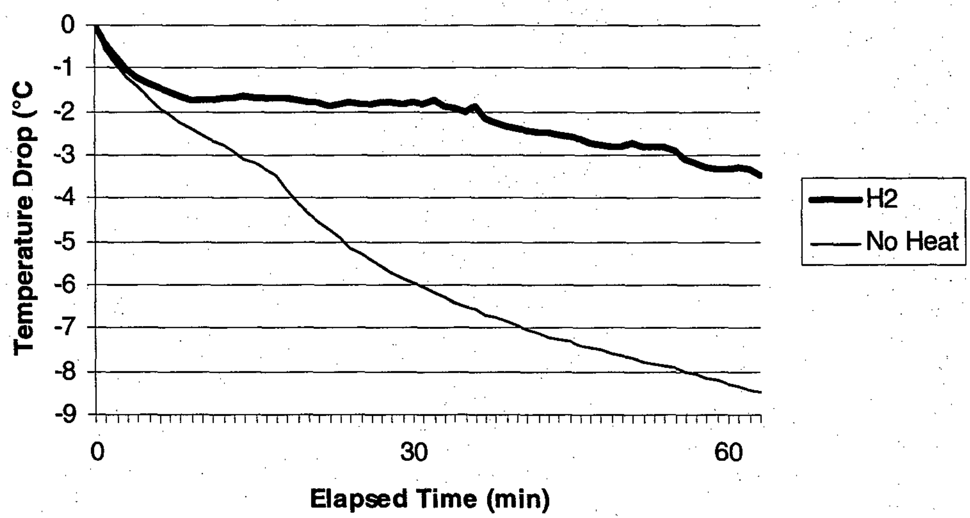


Figure 11. Mean thigh skin temperature (°C) drops from predive baselines with (H2) and without (No Heat) heating. Data is shown up to 63 min.

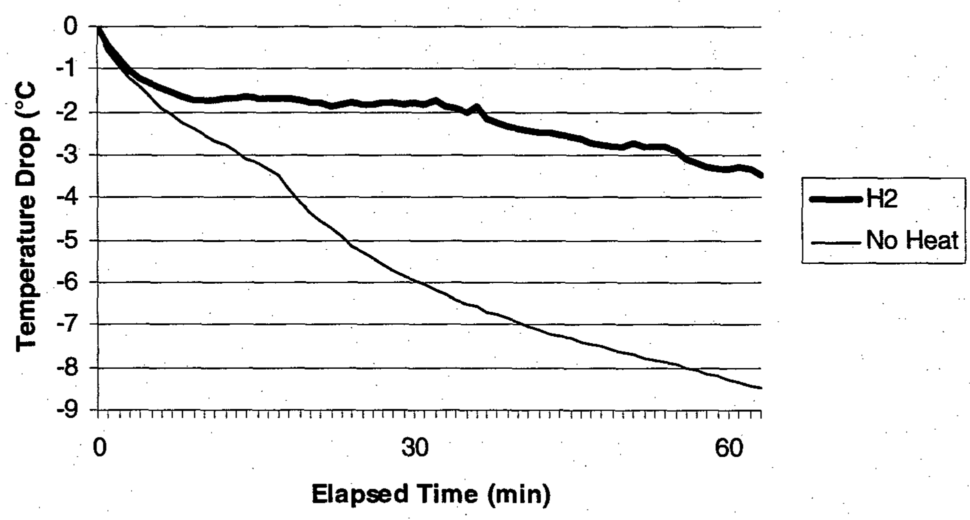


Figure 12. Mean calf skin temperature (°C) drops from predive baselines with (H2) and without (No Heat) heating. Data is shown up to 63 min.

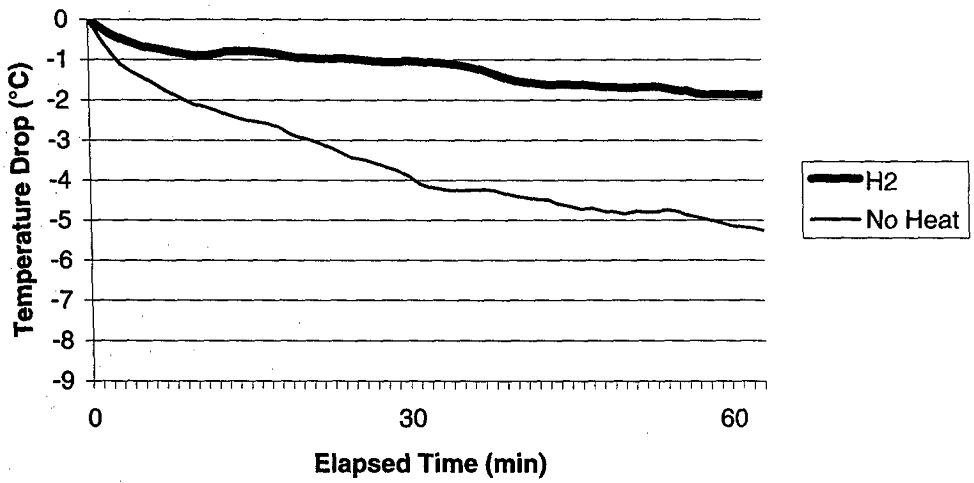


Figure 13. Mean upper arm skin temperature (°C) drops from predive baselines with (H2) and without (No Heat) heating. Data is shown up to 63 min.

IN-WATER QUESTIONNAIRE

Responses to thermal status questions 3–6 (Appendix B) were fairly consistent during the first hour of heated dives. During the first two questionnaire periods, mean thermal status ratings (questions 3–5) never fell below 4.0 on a 10-point cold-hot scale, and only 3/20 shivering ratings exceeded a score of 1 on a 10-point scale at the 60-minute interval.

POSTDIVE QUESTIONNAIRE

All the divers made comments (Appendix E) consistent with the general finding that, given adequate flow, the hydrogen catalytic heater and integrated tube suit provide adequate thermal protection. However, several divers commented that additional heating is needed in the hands and feet, particularly in the region of the heels. All divers reported that the three-finger glove limits their dexterity, a limitation that is not surprising because of the glove's design. Divers also identified suit bulk as a factor limiting their maneuverability, and some divers commented that they prefer integrating the heater and integrated tube suit with a semidry garment rather than a dry suit.

HEATER PERFORMANCE

Running logs (Appendix F) were maintained on each test day to observe how the prototype hydrogen catalytic heater responded when divers connected to and disconnected from the heating circuit. The heater control system is designed to automatically inject the required amount of hydrogen into the catalyst bed to maintain a preset water supply temperature (105 °F). As divers connect or disconnect with the

heating circuit, the system must increase or decrease the hydrogen injection rates to respond to varying heat load requirements on the heating circuit.

Figure 14 presents an example of delivered water temperatures and heat production rates provided by the prototype heater under varying heat loads. Complete test day narratives and heater profiles are provided in Appendix F. Note that numbers with arrows at the top of each chart serve as event markers. Time zero (Note 0) in Figure 14 indicates when the heater was initially started on that test day, with the circuit temperature controller set at 105 °F. The heater energy output was maximized at approximately 4000 watts to rapidly raise the circuit water temperatures, initially in equilibrium with the 37 °F test pool temperature, to 105 °F within approximately 10 minutes. As the circuit water temperature approached 105 °F, the heater reduced the energy output by automatically reducing hydrogen injection until the circuit temperature stabilized at 105 °F after an overshoot of approximately 4 °F. At Notes 1 through 5, divers entered the test pool and successively connected to the heating circuit (two divers connected simultaneously at Note 3). As more divers connected to the circuit, the increased heat loads initially caused drops in circuit temperature (approximately a 4 °F drop with two divers added), but a rapid increase in energy output returned the temperature to 105 °F within 2–3 minutes. On average, stabilized energy production rates increased approximately 250 watts for each diver added to the circuit.

At Note 8 the six divers simultaneously disconnected from the circuit to simulate lockout from an SDV. This disconnection initially resulted in a temperature overshoot of 5 °F and caused the heater to respond with a drop in energy output to less than 500 watts until the circuit temperature returned to 105 °F. At Note 9 the six divers reconnected to the circuit simultaneously, a sudden heat load increase causing the circuit temperature to drop to approximately 98 °F. The heater responded quickly by increasing its energy output to 4000 watts to bring the circuit temperature back to 105 °F within 10 minutes. Notes 11 through 21 show similar heater responses to circuit temperature fluctuations of 2–3 °F, as individual divers connected to and disconnected from the heating circuit.

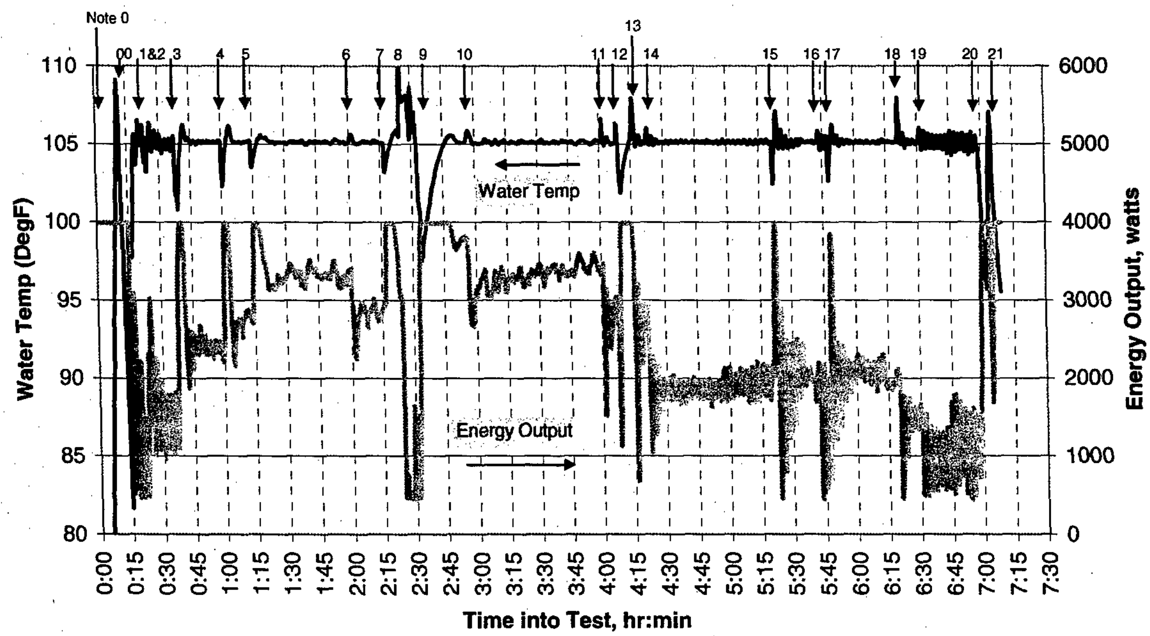


Figure 14. Heater response to varying heat loads on Test Day 5, as divers connected to and disconnected from the heating circuit (see Appendix F for details).

Table 7 summarizes statistics for heater performance when divers connected to and disconnected from the heating circuit.

Table 7.
Peak Changes in Heating Circuit Temperatures (°F) and Elapsed Times (min) to Stabilize the Circuit at 105 °F as a Function of the Number of Divers Connecting and Disconnecting.

Divers	Connect			Disconnect		
	N	Peak ↓ °F	Elapsed Time	N	Peak ↑ °F	Elapsed Time
1	20	2.38 1.56–3.20	2.15 1.37–2.93	26	1.58 1.22–1.94	2.15 1.56–2.74
2	7	3.20 1.86–4.54	2.71 1.83–3.59	3	3.00 1.12–4.88	2.67 1.00–6.46
4	4	5.28 2.48–8.07	3.25 1.25–5.25	4	3.75 2.16–5.34	11.00 4.00–18.00
6	1	7.50 NA	14.00 NA	1	5.6 NA	8.00 NA

Note: Mean temperatures and elapsed times (top) are reported with 95% confidence intervals (below).

The number of divers connecting to the heater circuit was significantly related to the peak *rise* in heater circuit temperature ($r = 0.74$, $p < .05$) and the time required to stabilize temperature at 105 °F ($r = 0.76$, $p < .05$). The number of divers disconnecting

from the heater circuit also was significantly related to the peak *drop* in heater circuit temperature ($r = 0.61$, $p < .05$) and the time required to stabilize temperature at 105 °F ($r = 0.62$, $p < .05$). These expected relationships and the data presented in Table 7 indicate that the heater circuit is a robust mechanism capable of responding to abrupt changes. Even when one diver with a faulty check valve connected to the heating circuit on Test Day 1 and caused a circuit temperature drop exceeding 30 °F (see Appendix F), the heater circuit stabilized the system 10 minutes after appropriate countermeasures were begun.

Figure 15 shows how mean skin temperatures changed as divers connected to and disconnected from the prototype heating circuit during the same test dive. As all six divers disconnected from the heating circuit (Note 8), a rapid drop in mean skin temperature resulted; this drop was followed by a similar rapid increase in mean skin temperature as they reconnected to the circuit. On average, the heating circuit maintained mean skin temperatures within a degree or two of baseline values throughout the dive except for divers #1 and #4, whose suits were found to be flooded after these divers had surfaced.

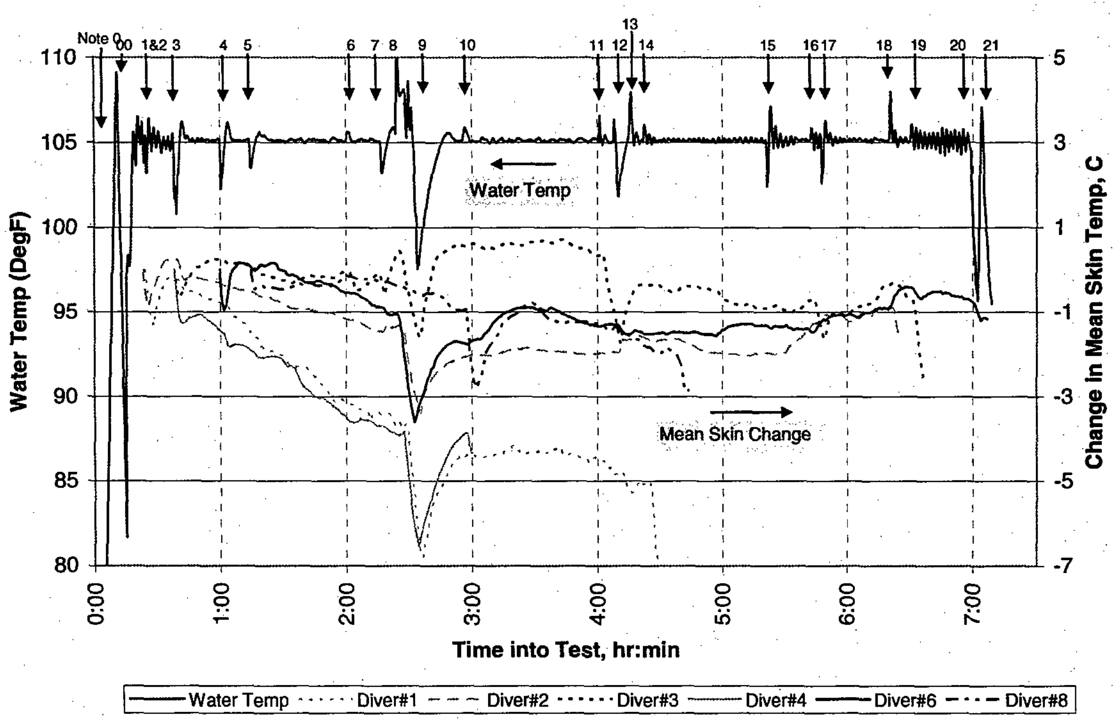


Figure 15. Change in divers' mean skin temperatures on Test Day 5 as they connected to and disconnected from the prototype heating circuit (see Appendix F for details).

Summary skin temperature statistics for divers connecting to and disconnecting from the hydrogen heater system are presented in Table 8. Regardless of the load on the system, the hydrogen heater effectively elevated mean skin temperatures when divers

connected to the circuit. As expected, mean skin temperatures fell when divers disconnected from the heater.

Table 8.
Maximum Changes in Mean Skin Temperature (°F) as a Function of the Number of Divers Connecting to and Disconnecting from the Hydrogen Heater.

Divers	Connect		Disconnect	
	N	Peak ↑ °F	N	Peak ↓ °F
1	2	1.30	2	−1.50
		1.30–1.30		−9.12 – 0
2	6	1.50	6	−1.83
		0.98–2.02		−2.65 – 0
4	24	2.10	24	−2.60
		1.73–2.46		−3.06 – 0
6	6	2.27	6	−2.37
		1.67–2.86		−2.96 – 0

Note: Mean skin temperatures (top) are reported with 95% confidence intervals (below). Maximum skin temperature changes were determined between connection and heater circuit stabilization (Connect), and between disconnection and subsequent reconnection (Disconnect).

DISCUSSION

The supplemental heating provided by the prototype hydrogen catalytic heater significantly increased dive durations. Mean dive duration with the heater and integrated tube suit was 145% longer than it was without heating. Mean heated dive duration was an additional 42% longer when divers wore aerogel finger and boot liners. To minimize the kinking of water supply tubes on the first two test days, we found no statistical difference between our modifications to the tube suit connectors inside the dry suit and diver training in donning the dry suit for Test Days 3–5; however, the statistical power for this comparison was <.80. Summary data suggest that dive duration may be enhanced with such modifications. Figure 16 shows typical tube kinking at the Q-D connectors for the two glove supply lines and the hood supply line during the first two test dives. These heating water supply restrictions presumably worsened as the tubing softened from the warm water flowing through the tubing after the divers had entered the test pool and connected to the heating circuit. Divers resolved such flow restrictions for Test Days 3–5 mostly by increasing their care in donning the garments to minimize tube kinking and by integrating the glove and hood supply lines into their tube suits to eliminate the Q-D connectors.

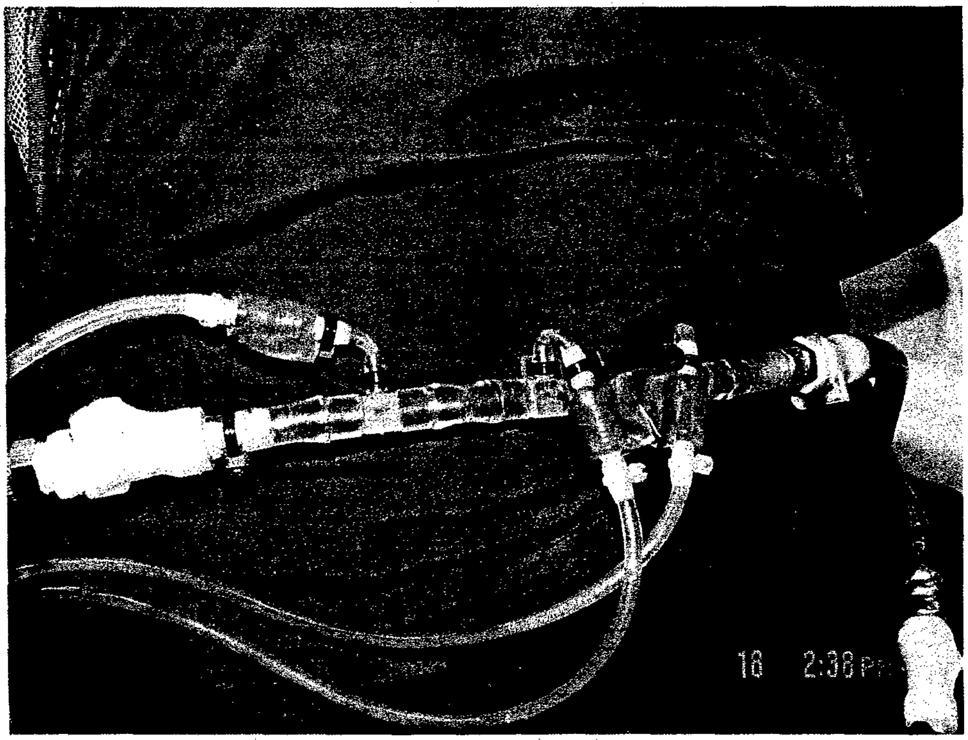


Figure 16. Flow restrictions due to tube kinking in integrated tube suits.

Of the 30 dives conducted with the prototype heater during the five test days, six divers remained for the entire six-hour planned exposure. At first glance this low ratio of dive completions could be interpreted as testimony that the prototype heater did not perform as planned. However, of the remaining 24 dives, five were aborted because of suit flooding, four were aborted because of confirmed flow restrictions in the tube suits, seven were aborted voluntarily by the divers due to physical discomfort from poor suit fit or an inoperable/full urine collection device, and one was aborted because of instrumentation failure. Only seven dives were aborted because of physical or reported thermal stress in the extremities (fingers, toes, hands, feet). Whether some or all of these thermal aborts were associated with unconfirmed tube kinking is unknown.

The results confirm that when adequate flow is maintained to the divers' tube suits, mean and localized reductions in skin temperature are more attenuated by using the prototype heater than by using the same garment with no heat. Using either Thinsulate or aerogel glove and boot liners in addition to heat from the heater also provided additional attenuated temperature reductions in the fingers. The divers did comment on one particularly cold region in the area of the heel that, even with unrestricted flow, appeared to be inadequately protected with the integrated tube suit. A survey of this region of the tube suits confirmed a low density of flow tubes in the heel. Future developments could maximize thermal protection in the extremities by increasing warm water flow to these regions through larger tube sizes or by providing additional flow channels.

The study confirmed that the heater is capable of delivering the heat capacity required to protect up to six divers simultaneously and of automatically adjusting the energy output to respond to variable heat loads as divers connect to and disconnect from the heating circuit. The heater was also found to be capable of automatically controlling the desired water supply temperature of 105 °F within approximately 0.5 °F when heat loads remained constant, and it proved to be capable of reacting within minutes to reestablish the desired circuit temperature following sudden temperature overshoots and reductions as divers connect to or disconnect from the heating circuit.

CONCLUSIONS / RECOMMENDATIONS

1. Dive duration in cold water (35–40 °F) was approximately 145% longer when divers were connected to the prototype heater (223 min) than when no heat was available through it (91 min).

2. The prototype heater substantially attenuates real-time finger, toe, chest, thigh, calf, and upper arm skin temperature reductions at the 60-minute dive interval. Adjustments in the warm water supply and tube spacing in the hands and feet may further enhance the thermal protection afforded by the prototype hydrogen heater.

3. Diver-subjects reported that the prototype heater provides adequate thermal protection as long as flow channels within the tube suit remain open. Further improvements to the tubesuit are necessary to ensure that flow restrictions due to tube kinking are minimized. Permanently attaching the tabulated gloves and hood to the tube suit garment helps to minimize flow restrictions at Q-D connectors.

4. The prototype heater controller is capable of maintaining a preset temperature of 105 ± 0.5 °F during periods of constant heat load — and of responding to sudden circuit temperature changes of 2–6 °F when divers connect to or disconnect from the heating circuit.

5. The prototype heater was found to be fully capable of supplying an energy output (up to 4000 watts) to provide adequate heating for one to six divers simultaneously and of automatically adjusting to varying heat loads as divers connect to and disconnect from the heating circuit. The time the required to raise heater circuit temperatures from a cold start at ambient water temperatures to 105 °F is approximately 10 minutes. Response time to restabilize circuit temperatures after divers connect to or disconnect from the circuit is often less than 6 minutes.

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APPENDIX A:
OPERATIONAL DESCRIPTION OF A DIVER HEATER FOR SDV APPLICATIONS USING HYDROGEN CATALYTIC REACTIONS

GAS CIRCUIT

The basic heater design uses a gas ejector pump to recirculate the gas inside an insulated fiberglass pressure vessel (three layers of AR5401 aerogel fabric insulation) in a semiclosed circuit mode shown schematically in Figure A-1. Air is supplied at 200 psig to a nozzle (orifice diameter 0.022") used in conjunction with a venturi (0.375" throat diameter) to generate the recirculatory flow of 6 actual ft^3/min inside the pressure vessel.

The fresh air injection rate into the pressure vessel is a constant 1.63 standard ft^3/min. The injected air provides a fresh oxygen supply rate of 0.34 standard ft^3/min. Exhaust gas (primarily nitrogen and water vapor) exits the pressure vessel through a backpressure regulator into the ambient water.

The backpressure regulator is set to maintain the pressure vessel at 100 psig. A safety relief valve (set at 125 psig) is located on the top end cap of the pressure vessel included in the heater design to relieve the internal pressure in case of a backpressure regulator failure.

Hydrogen is introduced at a variable flow rate to a maximum of 0.61 standard ft^3/min at the entrance of the gas ejector pump. In this manner the hydrogen is mixed inside the pressure vessel with the recirculated gas and the fresh incoming air to maintain a hydrogen level below 2% (well below the 4% combustion limit for hydrogen mixed in air).

After the gases are mixed, the recirculatory flow of 6 actual ft^3/min is passed through a canister containing a palladium catalyst on alumina pellets. In the presence of the catalyst, the hydrogen combines with the oxygen (from the fresh air supply) to produce water vapor and heat according to the reaction:

$$1H_2 + \frac{1}{2}O_2 \Rightarrow H_2O + 103{,}968\frac{Btu}{mol\,H_2}.$$

The gas temperatures generated inside the catalyst bed range from 150 °F to 350 °F, directly corresponding to the hydrogen injection rate. The recirculatory flow then passes through a gas-to-water heat exchanger where the heat is removed and some of the water vapor condenses. The recirculatory flow then returns to the entrance of the gas ejector pump, where the cycle is continually repeated.

The gas exiting the heat exchanger is primarily nitrogen, as most of the oxygen combines with the hydrogen in a ratio of 1 to 2 in the catalyst bed. A volume of gas equal to the incoming air flow rate (1.63 standard ft^3/min) is exhausted through the

backpressure regulator. In addition to this gas, any condensate also travels through the backpressure regulator, since the gas exit is on the bottom of the pressure vessel. The supply air travels from a high-pressure storage cylinder through a reducing regulator (with its outlet set at 200 psig) to a computer-controlled solenoid valve. From this air solenoid valve the air travels to the nozzle. The hydrogen is supplied from a high-pressure cylinder through a reducing regulator (with its outlet at 140 psig) to a computer-controlled solenoid valve. From this hydrogen solenoid valve the hydrogen flows through a computer-controlled micrometering valve (Nupro, product number [PN] SS-SS2-D) and then to the ejector pump entrance. Heater components are shown in Figures A-2 through A-4.

WATER CIRCUIT

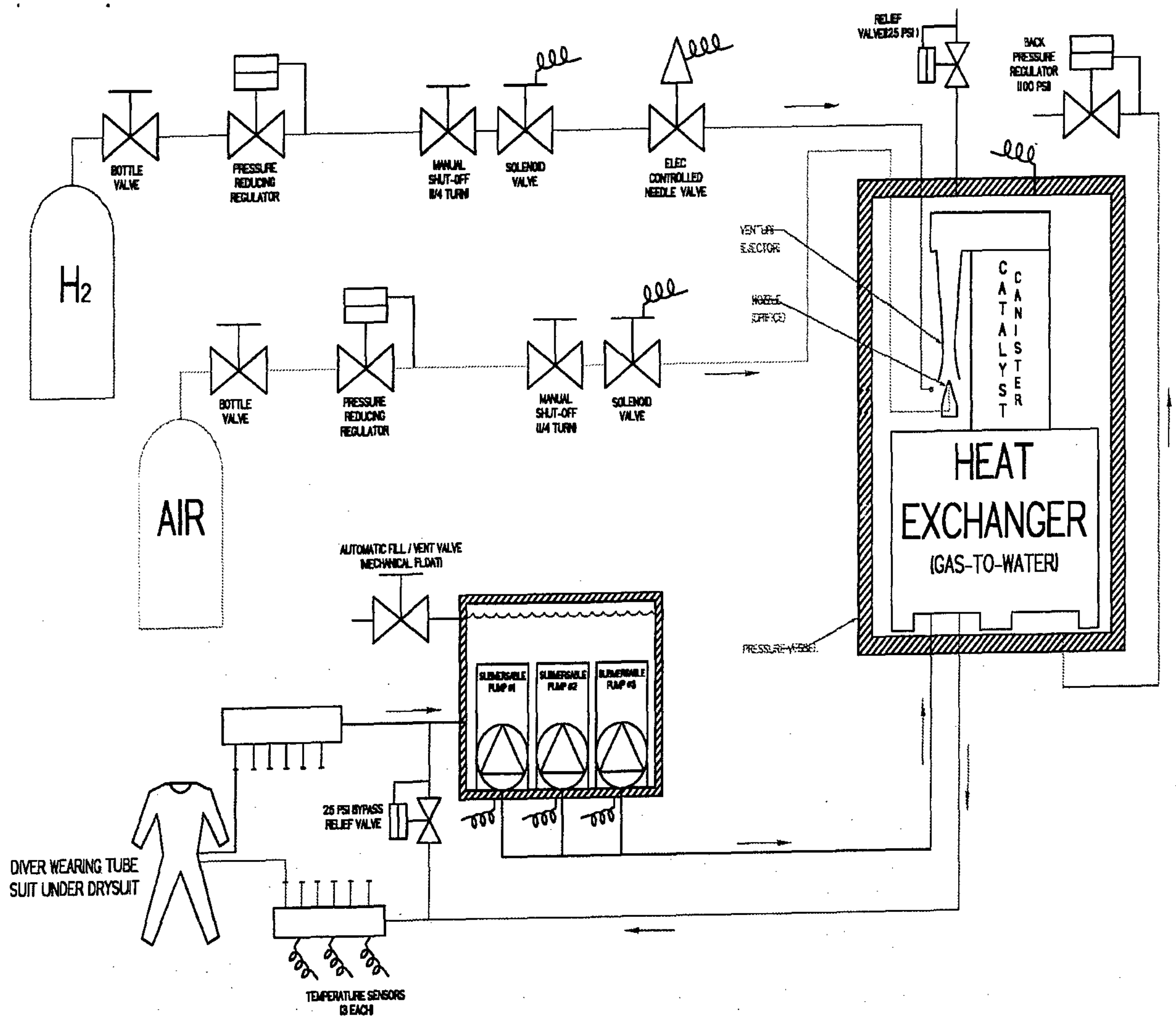
Water is circulated in a closed loop system by three 24 VDC submersible positive displacement pumps (ShureFlo, PN: 9325-043-101). Depending on the number of divers connected to the circuit, the pumps can be turned on in succession. This design also allows one of the pumps to fail while sufficient water flow (approximately 0.5–0.75 gal/min per diver) is still provided for all six divers. Located inside an insulated water reservoir (1.1 gal), the pumps move water from the reservoir through the catalyst pressure vessel via sealed hull penetrations. Three layers of AR5401 aerogel fabric provide the insulation for the pump reservoir. The water is heated inside the pressure vessel as it passes through the gas-to-water heat exchanger (see **GAS CIRCUIT**).

After heating, the water travels down an 8-foot (0.5 inch ID, 1.25 inch OD) supply water hose (Goodyear, PN: 6CDH04) to a custom plastic manifold. From this manifold, six 7-foot lengths of 0.25 inch ID insulated umbilicals supply heated water to the divers. A single layer of AR5401 aerogel fabric insulates these umbilicals. The extreme end of each umbilical is connected to the diver's suit via a quick-disconnect (QD) block to allow the diver to connect and disconnect, as needed, to make excursions from the SDV. The heated water travels from the QD block through a dry suit penetrator to the tube suit, where it is distributed throughout the diver's garment. The return water from the tube suit exits the dry suit and returns to the pump reservoir in a manner similar to that in which it proceeds through the supply water–dry suit penetrator, QD block, umbilical, return manifold, return hose, and back into the reservoir.

Inside the reservoir, a float valve allows any air in the water circuit to escape into the surrounding water to prevent the pumps from losing prime. Air could enter the system when a tube suit is connected to the circuit for the first time. In addition, the float valve allows makeup water to enter the closed loop system if losses occur from any accidental circuit leakage. Such leakage could occur when the diver is connecting to and disconnecting from the water circuit during lock-in or lockout from the SDV. The volume of the water in the circuit including all six tube suits is approximate 2.3 gal.

The water circuit also contains a pressure relief valve, located between the supply and the return manifolds, to limit the maximum water pressure supplied to the tube suits. If only one diver is connected to the circuit and all three positive displacement pumps are

on, the supply water pressure could exceed the tube suit limitation of 25 psi. At 20 psi, the relief valve opens between the two manifolds and bypasses the excess water flow to the return manifold so that no heated water is lost to ambient water. Figure A-5 shows the six parallel water circuits connected to divers' tube suits.



DIVERS HYDROGEN CATALYTIC HEATER SCHEMATIC (MECHANICAL)

Figure A-1. Schematic of hydrogen catalytic heater.

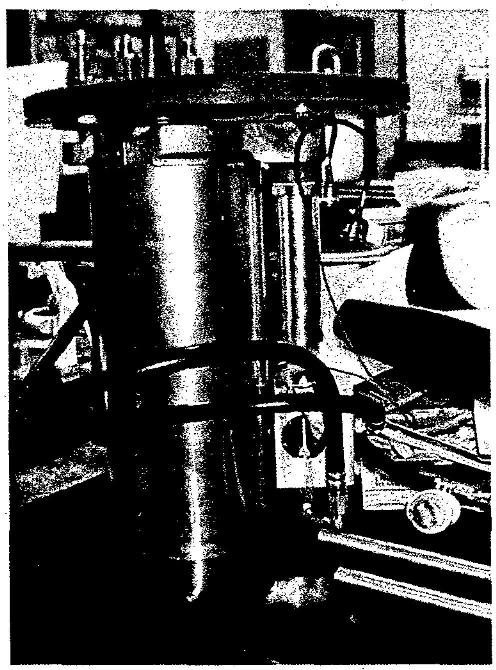


Figure A-2. Hydrogen catalytic heater prototype removed from the heater shell with the catalyst canister located in the upper half of the vertical cylinder, the air-to-water heat exchanger in the lower half of the vertical cylinder, and the gas injection system located on the right.

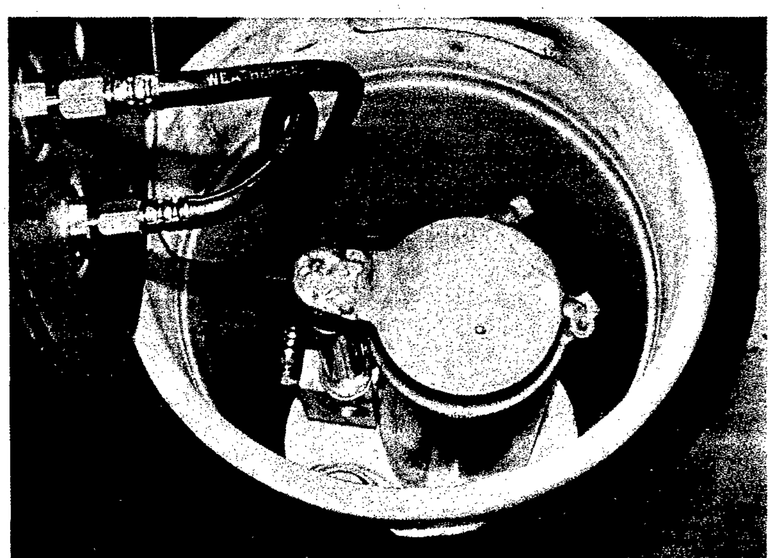


Figure A-3. Catalyst canister and gas ventilation system shown inside the SDV heater shell. The heat exchanger assembly is positioned beneath the catalyst canister.

Figure A-4. Prototype hydrogen catalytic heater and pump assembly with exterior insulation.

Figure A-5. Water distribution system consisting of 6 parallel water circuits and closed-circuit tubesuits connected to the prototype heater.

CONTROL SUBSYSTEM

A computer using a control feedback loop (Figure A-6) controls the water temperature and a stepper motor (Nippon, PN: PJB42S39B24) connected to the hydrogen micrometering valve to control hydrogen injection flow rates. Three temperature sensors (Yellow Spring Instruments, Model 402) located inside the supply water manifold supplies the control signals. A proportional-derivative (PD) control algorithm is used in a C language program to control the temperature by adjusting the hydrogen flow rate into the pressure vessel until the desired tube suit water temperature is achieved. If the circuit sensors detect that the water temperature is too high, the computer orders the hydrogen flow to be cut off. Conversely, if the temperature drops too low, hydrogen flow is increased by the computer directing the stepper motor to open the micrometering valve.

Three water temperature sensors provide redundancy to ensure the safety of the diver. To determine whether the readings are believable, the computer code allows each of the three water temperature sensors to "vote" on the actual temperature, then it takes the average on all that are found acceptable. This process minimizes the chances of burning a diver if one of the temperature sensors fails.

At the water circuit manifold an operator can preset the computer code for a desired maximum water temperature from 90 to 110 °F. If the water temperature exceeds 110 °F, the computer shuts the hydrogen solenoid and stops all the hydrogen injection.

An additional three temperature sensors are located inside the pressure vessel to record circulating gas temperatures. Two RTDs (Cole-Palmer, PN: RH-08117-96) record canister exit temperatures (averaged), and one thermistor (Yellow Spring Instruments, Model 402) records gas temperatures at the entrance to the ejector pump. In the unlikely event that the gas temperatures exiting the catalyst canister exceed 400 °F, the computer shuts the hydrogen solenoid and thereby stops all hydrogen injection. The custom software logs all sensor data and presents the output on a CRT display.

The computer also controls the power to all three pumps via a computer relay board. Inputs for the desired temperature setting and number of pumps are made through two rotary switches in a diver input control box. The computer, display, and power supply remain dry and on the surface. A 50-foot umbilical connects gas, electrical power, and sensors from the submerged heater to the surface. Depending on the number of pumps running, electrical power consumption is 70 to 190 watts: this includes the power to run the computer, water circulation pumps, and stepper control motor.

DIVERS HYDROGEN CATALYTIC HEATER SCHEMATIC (ELECTRICAL)

Electronic Parts List for Hydrogen Control system

Vendor	Description	Part No.
Ampro Inc.	Core Module 406 CPU PC104	4GV 16MB Dram 24 MB Disk on chip
Diamond Systems Corp.	Diamond-MM-16 A/D Board PC104 DC/DC power supply Board PC104	DMM-16-AT V104-512-V512
Analog Devices	Linearized RTD input Signal conditioner	5B34-04
YSI Corporation	Linearizing Circuit Thermistor Probe	4800LC-004 402
Nippon Pulse Motor	Motor Controller board PC104 Stepper Motor Stepper Motor Power Board	NPMC5023-2104 PJM42839R34 SMC-151
Quasar Electronics	Parallel port, 8 relay board	K3074
Cole-Parmer	RTD Temperature Probe	RH-08117-96

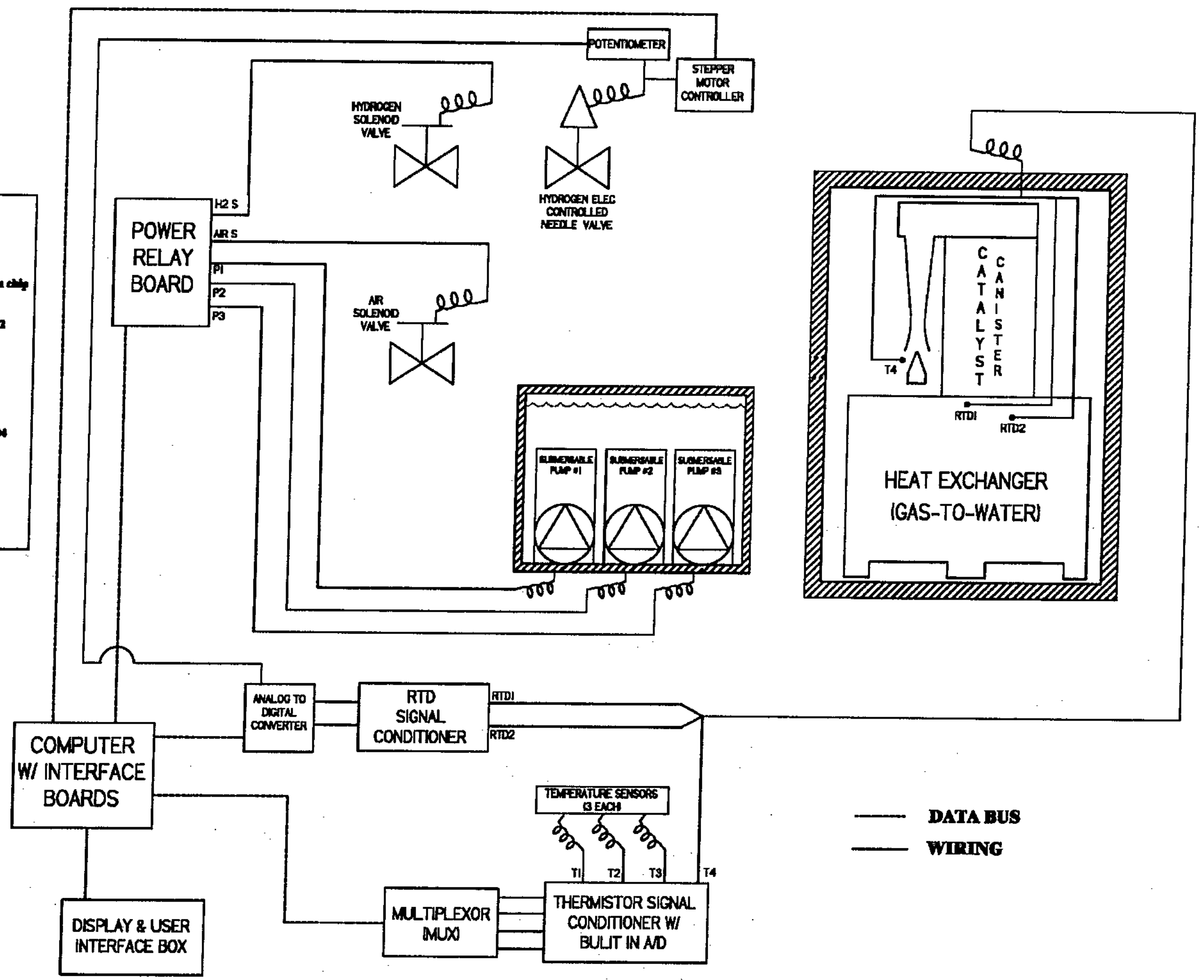


Figure A-6. Schematic of the control circuit.

APPENDIX B
IN-WATER DIVER THERMAL ASSESSMENT QUESTIONNAIRE

Test Date (DD/MMM/YY) ______________________ Time (HR:MIN) ______

Diver's Name (Last, First, M.I.) ______________________

1. ARE YOU COMFORTABLE?

1 2 3 4 5 6 7 8 9 **10**

Very Uncomfortable **Most Comfortable**

2. ARE YOU WET?

1 2 3 4 5 6 7 8 9 **10**

Completely Dry **Completely Wet**

3. ARE YOU COLD OR HOT?

1 2 3 4 **5** 6 7 8 9 **10**

Very Cold **Perfect** **Very Hot**

4. ARE YOUR HANDS COLD OR HOT?

1 2 3 4 **5** 6 7 8 9 **10**

Very Cold **Perfect** **Very Hot**

5. ARE YOUR FEET COLD OR HOT?

1 2 3 4 **5** 6 7 8 9 **10**

Very Cold **Perfect** **Very Hot**

6. ARE YOU SHIVERING?

1 2 3 4 5 6 7 8 9 **10**

Absent **Most Shivering**

7. IS THE LINER COMFORTABLE?

1 2 3 4 5 6 7 8 9 **10**

Least **Most Comfortable**

8. IS THE WATER IN THE LINER COLD OR HOT?

1 2 3 4 **5** 6 7 8 9 **10**

Very Cold **Perfect** **Very Hot**

9. DO YOU WISH TO QUIT SOON? ☐ YES ☐ NO

APPENDIX C
IN-WATER DIVER THERMAL ASSESSMENT QUESTIONNAIRE DATA

	Dive Interval (minutes)																	
	30									60								
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
#1-1	8	1	5	4	4	1	6	6	N	6	1	5	3	4	1	4	6	N
#2-1	8	1	5	5	5	1	8	5	N	8	1	5	5	4	1	8	4	N
#3-1	Dive aborted – faulty rectal probe																	
#4-1	6	1	4	3	3	1	7	5	N	Dive aborted – heater not connected								
#5-1	5	3	5	5	4	1	5	5	N	5	3	5	5	4	1	5	5	N
#6-1	8	1	5	5	4	1	8	5	N	8	1	5	5	4	1	8	5	N
#2-2	Dive aborted – flooded suit																	
#4-2	8	1	5	5	4	1	8	5	N	6	1	5	5	4	1	8	6	N
#6-2	9	1	5	5	5	1	9	4	N	9	1	5	5	5	1	9	5	N
#7-2	5	1	7	5	5	1	6	7	N	4	1	7	5	5	1	7	7	N
#8-2	6	4	5	5	4	1	9	4	N	5	5	5	5	2	1	8	5	N
#9-2	9	5	5	5	5	1	9	5	N	5	5	5	5	5	1	5	5	N
#1-3[a]	3	1	8	8	4	1	3	6	N	5	1	6	7	4	2	3	6	N
#2-3	7	3	5	5	5	1	8	5	N	7	2	4	5	4	2	7	3	N
#3-3[a]	6	1	5	5	4	1	6	5	N	6	1	5	5	4	1	5	5	N
#4-3	8	7	5	5	5	1	8	4	N	4	7	4	4	4	1	6	6	N
#6-3	4	1	5	5	4	1	7	5	N	7	1	5	5	4	5	7	5	N
#8-3	4	3	4	5	4	1	7	1	N	Dive aborted – toe temp/kink in tube suit								
#1-4	6	4	5	5	4	1	6	5	N	8	5	5	4	3	4	6	6	N
#2-4	7	1	4	4	4	1	8		N	7	1	5	5	4	1	7	5	N
#3-4	7	1	5	5	4	1	6	5	N	6	1	4	4	3	1	6		N
#4-4[a]	8	3	5	5	5	1	8		N	7	3	5	5	5	1	8	5	N
#6-4	8	1	4	5	4	1	8		N	6	1	4	3	3	2	8	3	N
#9-4[a]	Dive aborted – flooded suit																	
#1-5[a]	6	3	6	6	4	1	7	7	N	5	3	5	5	4	1	6	5	N
#2-5[a]	7	1	5	5	5	1	7	5	N	7	1	5	5	5	1	7	5	N
#3-5[a]	7	1	5	5	5	1	7	5	N	3	1	4	5	4	1	6	4	N
#4-5	8	1	5	5	5	1	8	5	N	8	1	4	4	4	1	7	4	N
#6-5	8	1	5	5	5	1	8	5	N	8	1	5	5	4	1	8	5	N
#8-5	3	1	5	4	5	1	8	7	N	3	1	5	4	4	1	8	5	N

Notes: Diver ID: test subject-test day; [a]heated dives with aerogel glove and boot liners; shaded Diver ID cells denote a dive with complications. Question numbers are indicated by Q#, per Appendix B.

APPENDIX D
POSTDIVE QUESTIONNAIRE

(1) How well did the liner fit? Please elaborate on any specific areas where the liner was too loose or tight, or where the fabric creased under your wet suit.

(2) Comment on your ability to move about and maneuver while wearing this liner. Easy? Difficult? Please elaborate on any specific maneuvers that were particularly difficult.

(3) How would you feel about using the system during a long (e.g., combat) swim? Please elaborate on how the system might interfere with a long swim.

(4) How well could you move your hands and manipulate objects while wearing the glove liners under wet suit gloves? Please elaborate on any specific activities that you found particularly difficult.

(5) What is your overall impression of this liner's ability to provide you with extra heat?

(6) Any suggestions for changing / improving the liner?

APPENDIX E: POSTDIVE COMMENTS

Diver ID	Dive	Garment	Cause for Abort	Comments
1	1	Thinsulate glove and boot liner	Finger Temp	Fit well, a little snug around left arm; was pinching tubing against arm maneuvering difficult due to bulk Glove dexterity poor Did not feel water flow to hands; finally wiggled and got some flow to my feet Suggest: trim rubber around jaw
1	3	Aerogel liners	Voluntary urine bag full	Suit fit well; difficult to maneuver, needed more weight; my hands were useless Impossible to do long swim--too much weight and bulky Could not manipulate objects with gloves; did manage to disconnect hose once w/o help Was comfortable as far as heat/warm; had difficulty putting air in drysuit--felt squeeze from tubing; became sore after first hour Just the tips of my fingers and toes become cold. The position of the hot water hose connection on Viking suit made it difficult to inflate suit.
1	4	Thinsulate	Voluntary/cold head/feet/ leak in suit	Suit fit well/comfortable today. Maneuvering was easier today; could grip enough to tighten hat straps Too bulky and too much weight for long swim Better dexterity today; was able to connect and disconnect own hose. Tubesuit did well, but went downhill fast after disconnecting from circuit; being wet on inside caused temperature to fall rapidly when unplugged Suggest: make ankle/heel area of drysuit bigger to aid dressing.
1	5	Aerogel liners	Voluntary/flooded lower suit	Suit fit well; difficult to maneuver/grasp with gloves Too bulky for a long swim Heater works well as long as none of the tubes become kinked Suggest: make ankle wider in drysuit
2	1	Thinsulate	Toe Temp	Medium tubesuit fit great under thinsulate Easy maneuvering, very comfortable Very warm when properly weighted and trimmed; training required for maximum comfort Glove dexterity poor Excellent source of extra heat, loved it! Suggest: use wet hood and gloves for max comfort and dexterity; manifold could use some grooming
2	2	Thinsulate	Flooded tubesuit	
2	3	Aerogel	Core abort/faulty sensor kink in tubesuit	Suit fit well; aerogel gloves and boots bulky and hard to get into boots Average maneuverability for a drysuit w/o fins Bulky for a long swim but manageable; laying flat would be more comfortable than verticle or sitting--feet get cramped Very limited dexteity; need better gloves for detailed work Felt no flow in tubesuit so extra heat was non existant Suggest: ankle area bulky; hose protectors or reinforced hose near connection to prevent kinking.
2	4	Thinsulate	Flooded suit/toe temp	Suit fit great and comfortable (Thinsulate); restrictive in leg when urine collection bag gets full; suggest overboard dump OK maneuverability for a drysuit; weight on ankles and keep a good seal on neck to prevent air into the hood Difficult for a long swim but doable; workups/training would be a must Dry gloves awkward but necessary for hot water suit Extra heat is good for core but poor in the feet/ OK in hands Suggest more tubes in feet
2	5	Aerogel	Completed dive	Aerogel components are beginning to loosen up and get more comfortable; tight fit in ankles when putting on shell Excellent maneuverability for a drysuit liner Bulky and heavy for a long swim, but do-able Gloves difficult to manipulate shackles, but could do it as long as hands were warm Tubesuit was a great source of supplemental heat; need more heat the longer you are in Suggest more heat to feet
3	1	Thinsulate	Faulty rectal probe	Liner fit well; dry suit needs bigger booties for all the undergarments maneuvering was easy little cumbersome for a long swim glove liners were great heat was good with exception of feet because of tight fit Suggest: larger feet on drysuit; limit extra hose connections on inside
3	3	Aerogel	Voluntary/urine bag full	Suit was too tight around feet and arm pits Maneuverability was good with exception of buoyancy Warmth was great Connecting and disconnecting was a little difficult with 3-finger gloves Tubesuit gave good heat; just need more around toes Suggest: encapsulate entire foot and have drysuit feet made larger
3	4	Thinsulate	Completed dive	Liner fit well Feet were tight; toes/bottom of feet need more heat Liner provided good core heat, just need more on feet Suggest: Integrate tubes into a foamy material like neoprene
3	5	Aerogel	Completed dive	Liner fit good; feet were a little tight Maneuvering was easy w/exception of buoyancy problems Swimming a short distance away from heater would work 3-finger gloves were cumbersome Extra heat was great Suggest: Encapsulate foot in tubes--incorporate tubes into foam like liner
4	1	Thinsulate	Hot water line was not connected!	System was bulky and tight; range of motion decreased due to bulkiness Long swim would be difficult Glove dexterity poor Construct hood of drysuit of less elastic material Locate hot water attachment to the front of suit so diver can see it.
4	2	Thinsulate	Finger temp	fit well; maneuvering was hindered more by buoyancy problems than fit of liner or drysuit impossible to make a long swim no dexterity with gloves the heat was adequate; never felt uncomfortably cold suggest: integrate gloves and hood; make less complicated donning and doffing; possibly try liner with semi-dry suit
4	3	Thinsulate	Toe temp	Liner fit well Liner didn't seem to limit motion Impossible for a long swim Dexterity is limited to picking up large objects Liner/heater work well Suggest: more heating in heel area; more durable tubing

4	4	Aerogel	Completed dive	Liner fit well Movement was hindered by liner Impossible for long swim Very little dexterity with 3-finger glove Heater worked well Suggest: make less bulky; integrate suit components; possibly use semi-drysuit
4	5	Thinsulate	Finger temp/ flooded left arm	Liner fit well Movement/dexterity was not hindered by the liner Impossible for long swim due to amount of weight needed and bulkiness of system 3-finger mitts made all but the simplest tasks impossible Bottom time would not be limited by water temperature when wearing this suit Suggest: use a semi-dry suit; wouldn't need urine catheter; buoyancy problems wouldn't be as great Semi-dry suit wouldn't compromise mission with a leaking suit Integrate system components to make easier to don/doff Attachment block should be modified so diver can attach and remove the hose with one hand w/o viewing it
5	1	Thinsulate	Voluntary/hood pressure on jaw	Liner fit OK; tight around ball of feet Easy manuevering Could swim OK if wearing a proper fitted drysuit, gloves and booties with lots of weight Gloves made it difficult to operate dump valve, fill valve and connect hot water hose Excellent suit when hoses are not crimped and good flow through the suit. Suggest: find way to keep tygon tubes from crimping/keep flow through tubes.
6	1	Thinsulate	Toe Temp	Liner fit well but had tube marks all over body after dive Liner did not restrict movement Would use system of a long swim Glove dexterity poor Believe tubing was kinked so heating was limited Suggest: anti-kinking sleeves for tubing
6	2	Thinsulate	Completed dive	liner fit well, but causes tube marks all over body but was overall comfortable maneuvering was as good as could be expected with the drysuit would use suit for long swim but more thought needs to be given to fix mandibular (jaw) discomfort any manual dexterity is difficult excellent heat provided, especially when set point on heater is raised (note: lowered set point at one point to get diver's opinion) suggest: add tubing to heals; put pouch for catheter bag on outside of liner on thigh
6	3	Thinsulate	Voluntary/urine bag full	Liner was not uncomfortable but I finished with tube marks all over my body Maneuverability is doable but need sufficient weight and practice System would work for a long swim Difficult to manipulate with hands System would be excellent if temperature was raised 5F
6	4	Aerogel	Finger temp/ kink in tubesuit	Liner fit well, some tube marks on body Suit needs sufficient weight to allow negative buoyancy with inflation I would use system during a long swim Dexterity greatly reduced with liner and 3-finger shell Heater was more than adequate barring dressing errors that caused tube restriction I used a loop of cloth and a 5 pound witht to hang over the top of my head to solve the chin discomfort from drysuit hood
6	5	Thinsulate	Completed dive	Liner fit well Maneuverability was difficult at first, easier with practice System good for long swim Almost no dexterity with gloves System excellent to provide extra heat Suggest: more tubing in heel area
7	2	Thinsulate	Voluntary/jaw pain	Liner perfect/comfortable fit! Maneuvering on surface is outstanding/difficult underwater when dry suit is donned swimming/buoyancy with suit will require training No dexterity with three finger gloves The liner is awesome. I was too hot. Suggest: Perhaps put a regulating valve at hot water block to slow flow down if you are too hot.
8	2	Thinsulate	Flooded suit	liner fit very well maneuvering was difficult because my drysuit was too small (note: used large suit--same as Robitalle) long swim would be difficult due to fit of hood which caused severe discomfort to my jaw bulkiness of suit in conjunction with lack of dexterity would hamper objectives gloves fit poorly; too much dead space and constantly came off of my fingers overall impression to provide heat was very good when used with tubesuit
8	3	Thinsulate	Toe temp/kink in tubesuit	Liner fit well Due to improper drysuit fit my mobility was very limited Hoses kink too easily; use stronger, more rigid tubing I think mobility would be OK in a wetsuit I made two dives; one my suit leaked, the other the hoses kinked and I had no flow Something must be done to prevent kinks Suggest: use armored hoses that will not kink; try using liner with wetsuit
8	5	Thinsulate	Voluntary/tight neckseal	Liner fit well; drysuit was too small Long swim would not be good Manipulating with hands not good in drysuit System is good for core, but poor for hands and feet
9	2	Thinsulate	Voluntary/cold feet	Liner fit extremely well. The hood may have been pulled out of place by the placement of the dry suit. Liner was easy to maneuvering in. Dry suit was too small and restricted movement. I would love to try this system with a lightweight wet suit. I believe that it provides great comfort to head, hands and feet. Drysuit lobster claws sucked. If system was commercially available, I would buy one today. A kink or vapor lock switched water off my feet after we disconnected and reconnected the suit.
9	4	Aerogel	Flooded suit	Liner was too tight in arms and shoulders. Drysuit did not fit well over liner, causing bunching and pulling Maneuvering difficult due to shoulder tightness I would like to try the system with a wetsuit or Mare's semi-dry Lobster claw gloves limited mobility Suit flooded in less than 5 min due to malfunction

APPENDIX F. RUNNING NARRATIVES OF HEATER TESTING

Running Narrative of NEDU Heater Testing
Day 1 – 18 Jan 2005

Time Into Test, hr:min	Event
0:00	0—Start heater and start logs
0:54	1—Divers #5 and #6 plugged into hot water circuit
1:25	2—Divers #3 and #4 plugged into hot water circuit; Diver #4 has his tube suit connection short-circuited—not receiving warm water
1:40	3—Temporarily raised circuit set point temperature to 110 °F
1:43	4—Reset circuit set point temperature to 105 °F
1:52	5—Diver #3 aborted due to faulty rectal probe
2:16	6—Divers #1 and #2 plugged into hot water circuit
2:18	7—Diver #4 aborted due to low finger temperature; received no heating as a result of failure to properly connect to heating circuit
2:43	8—Check valve in one of the unused circuits (either #3 or #4) failed, dumping hot water out of the system and pulling in cold water; circuit temperature fell to 61 °F before divers switched to unused circuits to stop water loss.
3:01	9—Divers #1, #2, #5, and #6 disconnect; reconfirm that circuit leak through faulty check valve causing temperature drop
3:06	10—Trouble shoot of circuit finds faulty check valve; all four divers reconnect to circuit
3:31	11—Diver #6 aborted due to low finger/toe temperature; 3 divers on circuit
4:15	12—Diver #1 aborted due to low finger temperature; 2 divers on circuit
4:43	13—Diver #2 aborted due to low toe temperature; 1 diver on circuit
5:37	14—Diver #5 voluntarily aborts due to jaw pain

Day #1: Heater response to variable diver loading.

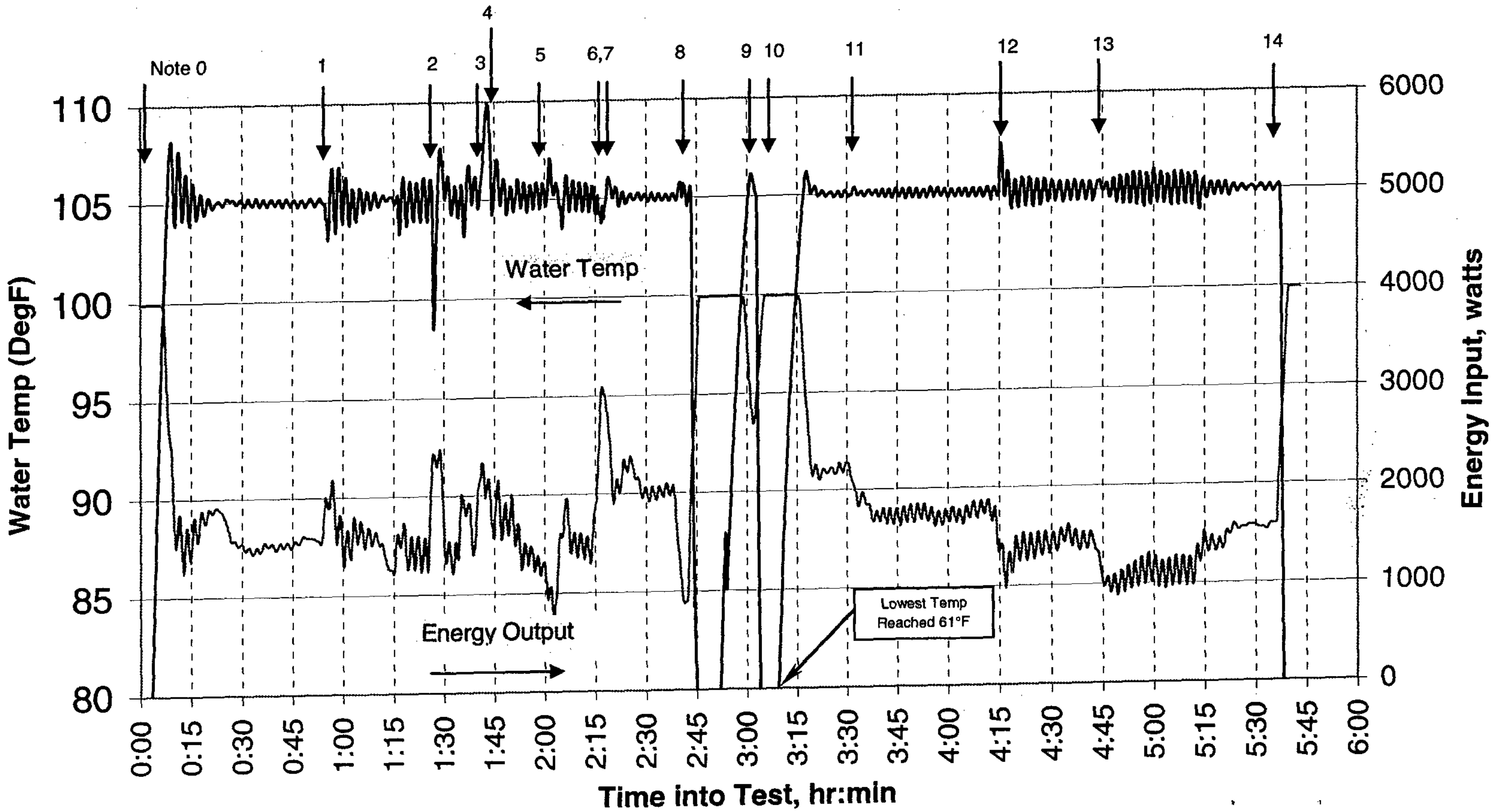
Notes:

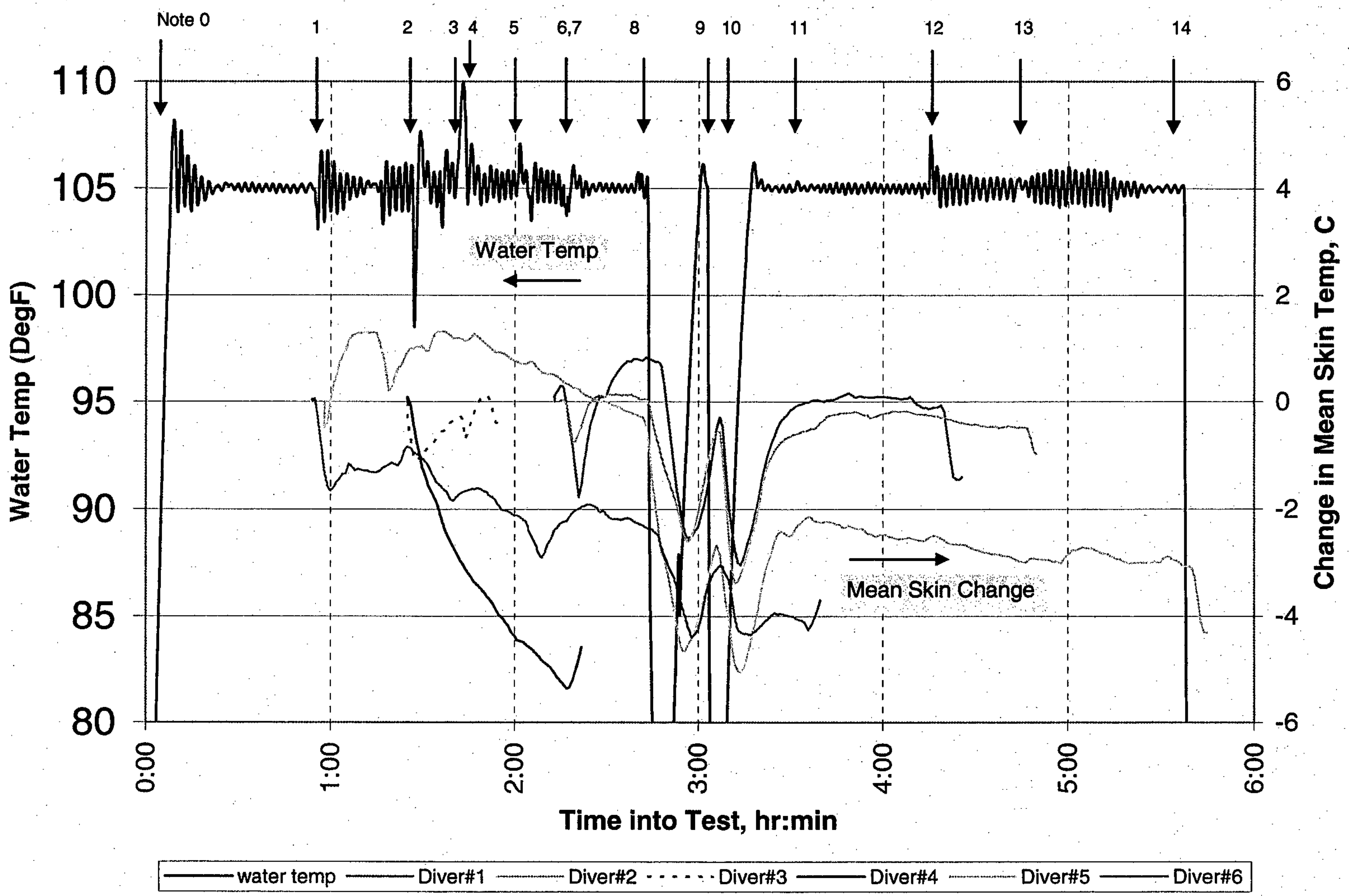
0—Start heater and start logs

1—Divers #5 and #6 plugged into hot water circuit

2—Divers #3 and #4 plugged into hot water circuit; Diver #4 has his tube suit connection short-circuited—not receiving warm water
3—Temporarily raised circuit set point temperature to 110 °F
4—Reset circuit set point temperature to 105 °F
5—Diver #3 aborted due to faulty rectal probe
6—Divers #1 and #2 plugged into hot water circuit

7—Diver #4 aborted due to low finger temperature; received no heating as a result of failure to properly connect to heating circuit
8—Check valve in one of the unused circuits (either #3 or #4) failed, dumping hot water out of the system and pulling in cold water; circuit temperature fell to 61 °F before divers switched to unused circuits to stop water loss.
9—Divers #1, #2, #5, and #6 disconnect; reconfirm that circuit leak through faulty check valve causing temperature drop
10—Troubleshoot of circuit finds faulty check valve; all four divers reconnect to circuit
11—Diver #6 aborted due to low finger/toe temperature; 3 divers on circuit
12—Diver #1 aborted due to low finger temperature; 2 divers on circuit
13—Diver #2 aborted due to low toe temperature; 1 diver on circuit
14—Diver #5 voluntarily aborts due to jaw pain





Day #1: Effect of water circuit temperatures on mean skin temperatures

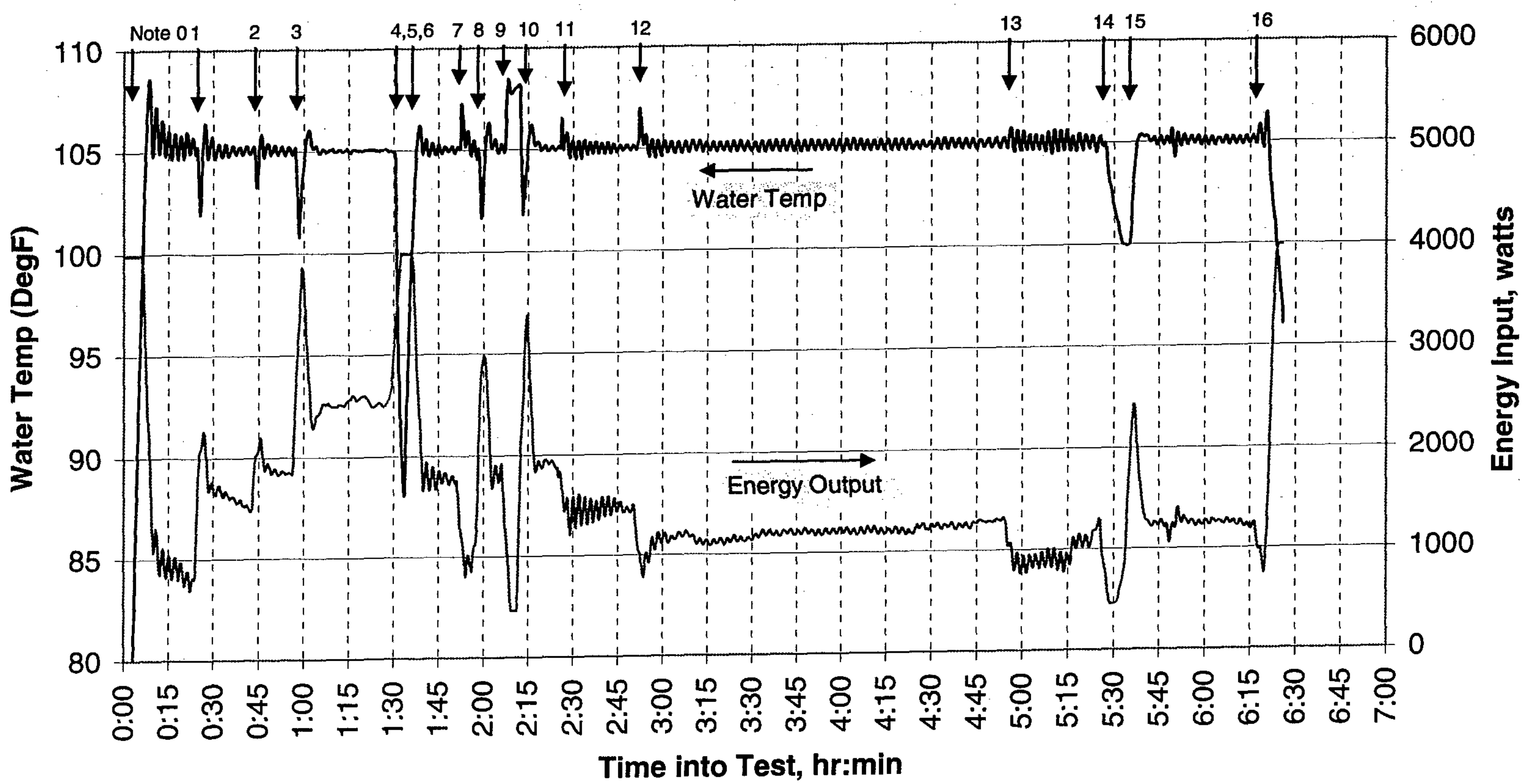
Running Narrative of NEDU Heater Testing

Day 2 – 20 Jan 2005

Water Temp: 37.8 °F
H_2 Supply Pressure: 180 psi
Air Supply Pressure: 250 psi

Computer Time	Time Into Test, hr:min	Event
0816	**0:00**	**0—Start heater and start logs (H_2 bottle press = 2075psi)**
0818	0:02	Start logging data
0824	0:08	9.8% O_2 (water temp @100 °F)
0825	0:09	water temp @105 °F
0827	0:11	7.4% O_2 in exhaust gas
0834	0:18	Splash Diver #8
0840	0:24	Splash Diver #6
0842	0:26	16.1% O_2 in exhaust
0843	**0:27**	**1—Divers #6 and #8 plugged into hot water circuit**
0854	0:38	13.3% O_2 in exhaust (H_2 bottle press = 1910 psi)
0902	**0:46**	**2—Diver #4 plugged into hot water circuit**
0915	**0:59**	**3—Diver #9 plugged into hot water circuit; switch to 2 pumps; 4 on circuit**
0929	1:13	8.9% O_2 (H_2 bottle press = 1750 psi)
0948	**1:32**	**4—Diver #2 plugged into hot water circuit**
0950	**1:34**	**5—Diver #7 plugged into hot water circuit; 6 on circuit**
0953	**1:37**	**6—Divers #2 and #8 abort; Diver #8 had flooded suit, Diver #2 had tube suit failure; 4 on circuit; 2 pumps**
1005	1:49	10.7% O_2 (H_2 bottle press = 1520 psi)
1009	1:53	11.2% O_2 (H_2 bottle press = 1510 psi)
1010	**1:54**	**7—Divers #4 and #6 disconnect; 2 on circuit; 1 pump**
1016	**2:00**	**8—Divers #4 and #6 reconnect; 4 divers on circuit**
1025	**2:09**	**9—All 4 divers disconnect; 0 divers on circuit**
1030	**2:14**	**10—4 divers reconnect into hot water circuit; 4 divers on circuit**
1041	2:25	11.5% O_2 (H_2 bottle press = 1400 psi)
1044	**2:28**	**11—Diver #9 voluntarily aborts due to cold feet; 3 divers on circuit; 2 pumps**
1108	**2:52**	**12—Diver #7 voluntarily aborts due to jaw pain; 2 divers on circuit; switched to 1 pump**
1136	3:20	14.9% O_2 (H_2 bottle press = 1250 psi)
1211	3:55	14.7% O_2 (H_2 bottle press = 1125 psi)
1247	4:31	14.4% O_2 (H_2 bottle press = 1010 psi)
1312	**4:56**	**13—Diver #4 aborts due to finger temp; 1 diver left on circuit;** (H_2 bottle press = 950 psi)
1320	5:04	15.4% O_2

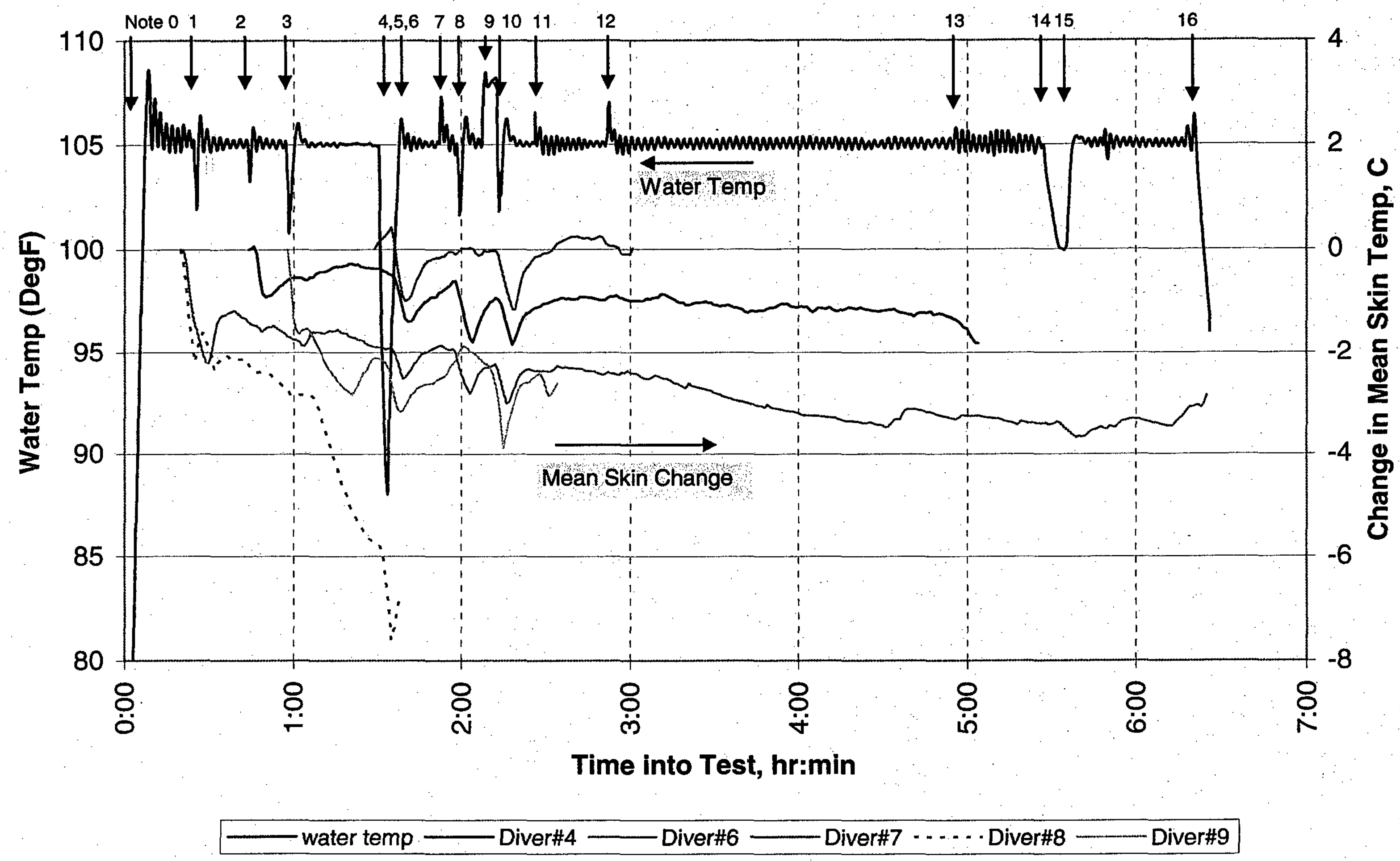
1322	5:06	15.6% O_2
1333	5:17	15.0% O_2 (H_2 bottle press = 900 psi; changed H_2 injection pressure to 170 psi)
1341	5:25	16.0% O_2 (changed H_2 injection pressure to 160 psi)
1344	**5:28**	**14—Changed water temp set point to 100 ^{o}F; 1 diver on; 1 pump**
1353	**5:37**	**15—Changed water temp set point back to 105 ^{o}F**
1428	6:12	15.8% O_2
1436	**6:20**	**16—Diver #6 completes dive and surfaces**
1437	6:21	Heater turned off (H_2 bottle press = 800 psi)



Day #2: Heater response to variable diver loading.

Notes:

0—Start heater and start logs (H_2 bottle press = 2075psi)
1—Divers #6 and #8 plugged into hot water circuit
2—Diver #4 plugged into hot water circuit
3—Diver #9 plugged into hot water circuit; switch to 2 pumps; 4 on circuit
4—Diver #2 plugged into hot water circuit
5—Diver #7 plugged into hot water circuit; 6 on circuit
6—Divers #2 and #8 abort; Diver #8 had flooded suit, Diver #2 had tube suit failure; 4 on circuit; 2 pumps
7—Divers #4 and #6 disconnect; 2 on circuit; 1 pump
8—Divers #4 and #6 reconnect; 4 divers on circuit
9—All 4 divers disconnect; 0 divers on circuit
10—4 divers reconnect into hot water circuit; 4 divers on circuit
11—Diver #9 voluntarily aborts due to cold feet; 3 divers on circuit; 2 pumps
12—Diver #7 voluntarily aborts due to jaw pain; 2 divers on circuit; switched to 1 pump
13—Diver #4 aborts due to finger temp; 1 diver left on circuit; (H_2 bottle press = 950 psi)
14—Changed water temp set point to 100 °F; 1 diver on; 1 pump
15—Changed water temp set point back to 105 °F
16—Diver #6 completes dive and surfaces



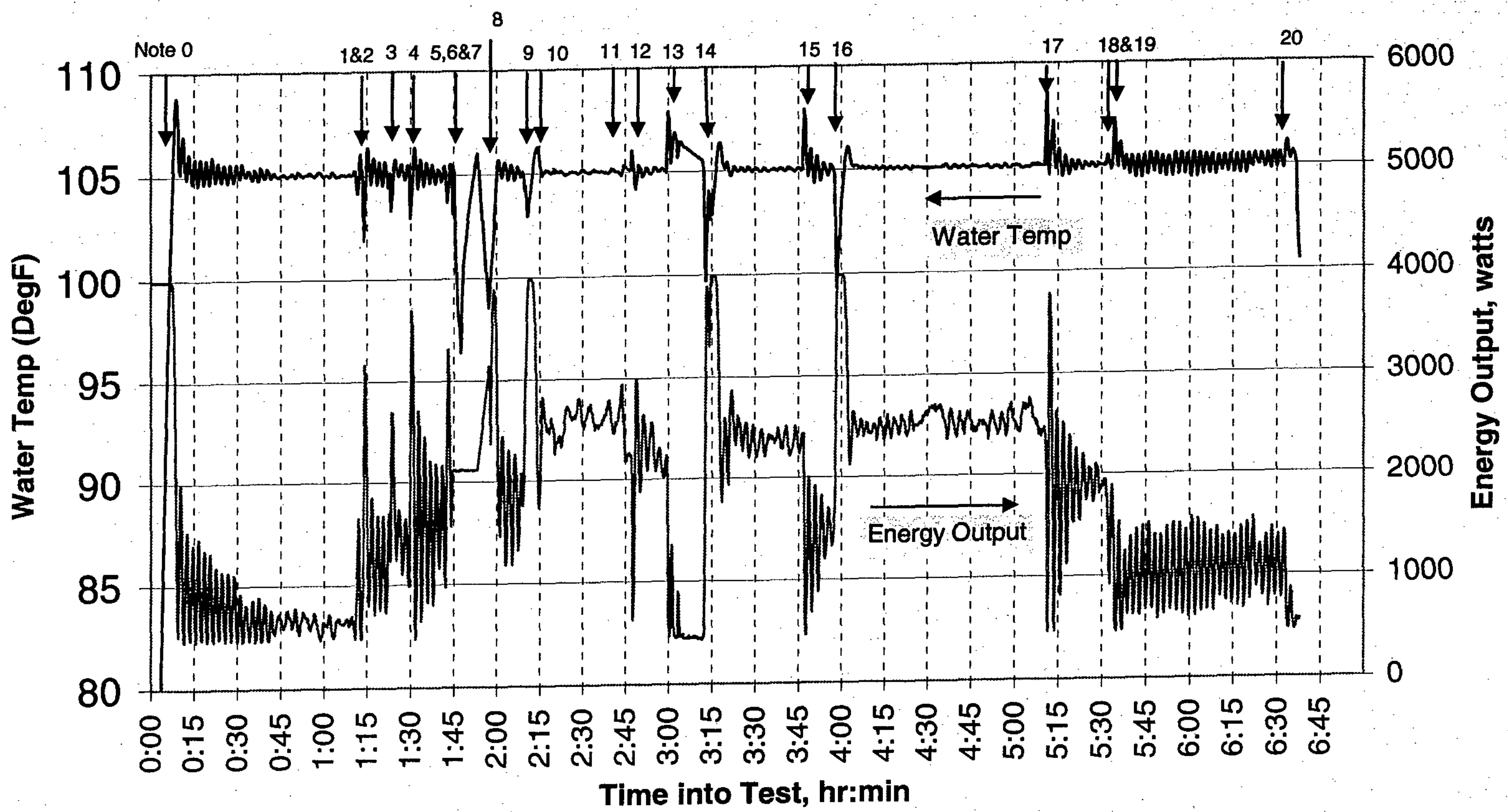
Day #2: Effect of water circuit temperatures on mean skin temperatures.

Running Narrative of NEDU Heater Testing
Day 3 – 14 Feb 2005

Water Temp: 38 °F
H_2 Supply Pressure: 180 psi
Air Supply Pressure: 250 psi

Computer Time	Time Into Test, hr:min	Event
0800	**0:00**	**0—Start heater and start logs (H_2 bottle press = 2100psi)**
0816	0:16	13.1% O_2 exit; water temp @ 105 °F
0830	0:30	16.5% O_2 (H_2 bottle press = 1960 psi)
0845	0:45	17.1% O_2 (H_2 bottle press = 1910 psi)
0855	0:55	Splash Diver #1
0900	1:00	17.2% O_2 (H_2 bottle press = 1900 psi)
0901	1:01	Splash Diver #2
0911	**1:11**	**1—Diver #2 plugged into hot water circuit**
0914	**1:14**	**2—Diver #1 plugged into hot water circuit**
0920	1:20	Splash Diver #4
0921	1:21	Splash Diver #3
0922	1:22	14.7% O_2 (H_2 bottle press = 1820 psi)
0924	**1:24**	**3—Diver #3 plugged into hot water circuit**
0926	**1:26**	**4—Diver #4 plugged into hot water circuit**
0929	1:29	Switched to 2 pumps; 13.8% O_2 (H_2 bottle press = 1800 psi)
0939	1:39	Splash Diver #8
0940	1:40	Splash Diver #6
0943	**1:43**	**5—Diver #6 plugged into hot water circuit**
0944	**1:44**	**6—Diver #8 plugged into hot water circuit**
0945	**1:45**	**7—Diver #4 unplugged from circuit; 2 pumps on**
0948	**1:48**	**8—Hydrogen supply automatically turns off**
0954	1:54	Rebooted computer (Restart water temp @ 95 °F)
0957	1:57	Computer starts logging again
1008	2:08	Diver #4 resplash (slight leak found in dry suit plus tube suit lines were kinked. Tube suit fixed; dry suit leak not fixed.)
1010	**2:10**	**9—Diver #4 plugged into hot water circuit again; all six divers on circuit. 3 pumps on**
1019	**2:19**	**10—Diver #8 unplugged from circuit. Suspect kinked tube in tube suit. Brought to surface. 5 divers on circuit**
1025	2:25	8.5% O_2 (H_2 bottle press = 1560 psi); 3 pumps on
1027	2:27	Confirmed Diver #8 had kinked main water supply tubes
1030	2:30	8.8% O_2 (H_2 bottle press = 1520 psi)
1038	**2:38**	**11—Diver #8 resplash and plugs into hot water circuit; 6 divers on circuit**
1044	**2:44**	12—Diver #2 aborted due to core temperature (suspect

		faulty rectal probe); 5 divers on circuit
1047	2:47	Switch to 2 pumps
1051	2:51	Diver #8 reports on flow apparent in tube suit; Diver #2 had kink in tube suit confirmed
1100	**3:00**	**13—Divers #1, #3, #4, and #6 unplug from circuit; 1 pump on; Diver #8 on circuit but reports no flow (kink?)**
1113-1115	**3:13-3:15**	**14—4 divers reconnect to circuit; Diver #8 disconnects and aborts due to toe temp; switch to 2 pumps; 4 divers on circuit**
1116	3:16	Confirmed Diver #8 had kink in tube suit supply
1125	3:25	9.4% O_2 (H_2 bottle press = 1300 psi)
1133	3:33	9.6% O_2 (H_2 bottle press = 1250 psi)
1143	3:43	9.7% O_2 (H_2 bottle press = 1210 psi)
1147	**3:47**	**15—Divers #1 and #3 disconnect from circuit; switch to 1 pump; 2 divers on circuit**
1158	**3:58**	**16—Divers #1 and #3 reconnect to circuit; 4 divers on circuit; switch to 2 pumps**
1215	4:15	9.1% O_2 (H_2 bottle press = 1160 psi)
1300	5:00	9.3% O_2 (H_2 bottle press = 810 psi)
1311	**5:11**	**17—Diver #4 aborted due to toe temp; 3 divers on circuit; 2 pumps**
1333	**5:33**	**18—Diver #6 voluntarily aborts due to full urine bag; 2 divers on circuit; switched to 1 pump**
1336	**5:36**	**19—Diver #1 voluntarily aborts due to full urine bag and discomfort with dry suit hood; 1 diver on circuit**
1353	5:53	15.4% O_2 (H_2 bottle press = 610 psi)
1437	**6:37**	**20—Diver #3 voluntarily aborts due to general chin and ear discomfort (mild) and full urine bag; test terminated**
		Plan: fix Diver #4 dry suit leak; switch back to DUI dry suits for Divers #1 and #8



Day #3: Heater response to variable diver loading.

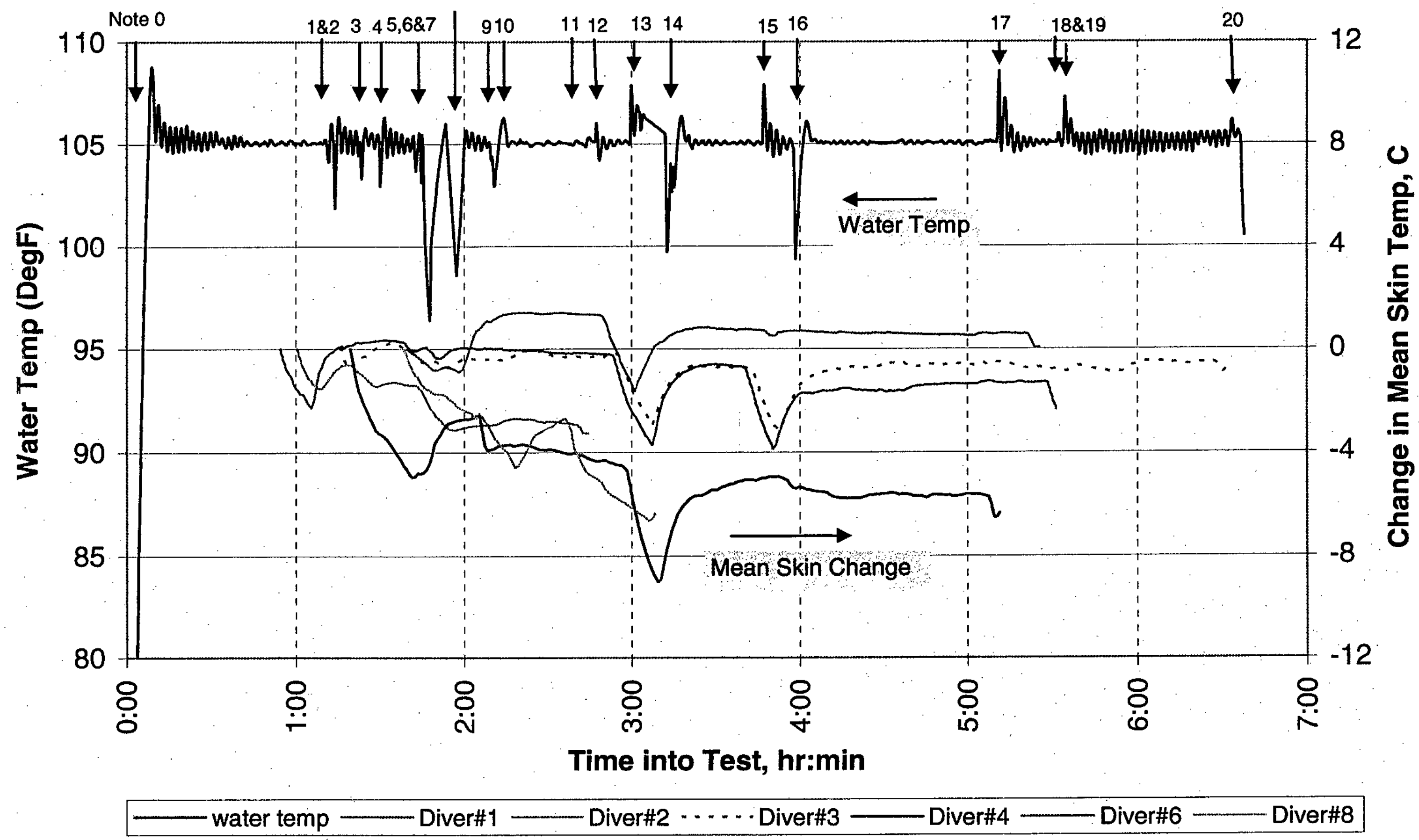
Notes:

0—Start heater and start logs (H_2 bottle press = 2100psi)
1—Diver #2 plugged into hot water circuit
2—Diver #1 plugged into hot water circuit
3—Diver #3 plugged into hot water circuit

4—Diver #4 plugged into hot water circuit
5—Diver #6 plugged into hot water circuit
6—Diver #8 plugged into hot water circuit
7—Diver #4 unplugged from circuit; 2 pumps on
8—Hydrogen supply automatically turns off
9—Diver #4 plugged into hot water circuit again; all six divers on circuit. 3 pumps on

10—Diver #8 unplugged from circuit. Suspect kinked tube in tube suit. Brought to surface. 5 divers on circuit

11—Diver #8 resplash and plugs into hot water circuit; 6 divers on circuit
12—Diver #2 aborted due to core temperature (suspect faulty rectal probe); 5 divers on circuit
13—Divers #1, #3, #4, and #6 unplug from circuit; 1 pump on; Diver #8 on circuit but reports no flow (kink?)
14—4 divers reconnect to circuit; Diver #8 disconnects and aborts due to toe temp; switch to 2 pumps; 4 divers on circuit
15—Divers #1 and #3 disconnect from circuit; switch to 1 pump; 2 divers on circuit
16—Divers #1 and #3 reconnect to circuit; 4 divers on circuit; switch to 2 pumps
17—Diver #4 aborted due to toe temp; 3 divers on circuit; 2 pumps
18—Diver #6 voluntarily aborts due to full urine bag; 2 divers on circuit; switched to 1 pump
19—Diver #1 voluntarily aborts due to full urine bag and discomfort with dry suit hood; 1 diver on circuit
20—Diver #3 voluntarily aborts due to general chin and ear discomfort (mild) and full urine bag; test terminated



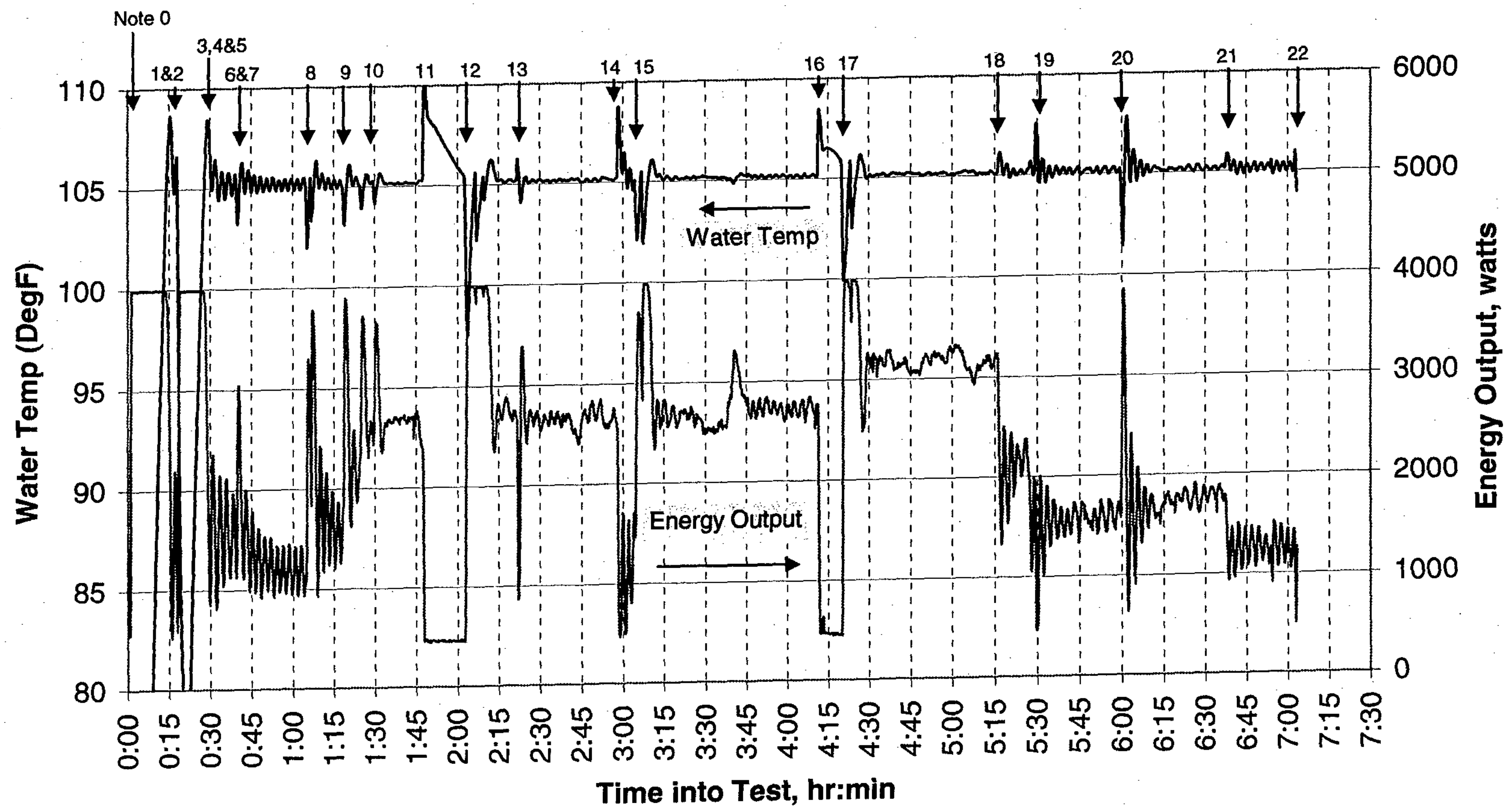
Day #3: Effect of water circuit temperatures on mean skin temperatures.

Running Narrative of NEDU Heater Testing
Day 4 – 16 Feb 2005

Water Temp: 35 °F
H_2 Supply Pressure: 180 psi
Air Supply Pressure: 250 psi

Computer Time	Time Into Test, hr:min	Event
0810	**0:00**	**0—Start heater and start logs (H_2 bottle press = 2100psi)**
0815	0:05	13.3% O_2 exit; water temp @ 61 °F
0818	0:08	10.0% O_2 (water temp @77 °F, catalyst bed temp @ 278 °F)
0822	0:12	14.4% O_2 (water temp @99 °F, catalyst bed temp @ 275 °F)
0824	0:14	16.3% O_2 (water temp @105 °F, catalyst bed temp @ 278 °F)
0825	0:15	Splash Diver #6
0826	0:16	Splash Diver #9
0828	**0:18**	**1—Diver #6 and #9 plugged into hot water circuit; circuit temp drops to 70 °F due to apparent circuit leak**
0830	**0:20**	**2—Diver #6 disconnects and returns to surface to adjust hood**
0835	**0:25**	**3—Diver #6 reconnects**
0836	**0:26**	**4—Diver #9 disconnects and returns to surface to replace finger sensor**
0838	0:28	Water circuit back up to 105 °F (Note: Diver #6 apparently had a bad initial connection with circuit causing water temp to drop; after he disconnected at 0830, temp began rising.)
0842	**0:32**	**5—Diver #9 reconnected to circuit; 2 divers on circuit**
0846	0:36	Splash Diver #4
0849	**0:39**	**6—Diver #4 plugged into circuit; 3 divers on**
0850	**0:40**	**7—Diver #9 aborts due to flooded suit and cold feet; 2 divers on circuit**
0911	1:01	Splash Diver #3
0915	**1:05**	**8—Diver #3 plugged into hot water circuit; 3 divers on circuit; switched to 2 pumps**
0925	1:15	Splash Diver #1
0928	**1:18**	**9—Diver #1 plugged into hot water circuit; 4 divers on**
0932	1:22	Splash Diver #2
0934	**1:24**	**10—Diver #2 plugged into hot water circuit; 5 divers on circuit; switched to 3 pumps**
0957	1:47	Switched to 1 pump prior to locking out 4 divers
0958	**1:48**	**11—Divers #1, #2, #3, and #4 disconnect from hot water circuit; 1 diver on circuit; circuit temp rise to 108 °F**
1012	2:02	Circuit temp back down to 105.3 °F
1013	**2:03**	**12—Divers #1, #2, #3, and #4 reconnect to circuit; 5 divers on; circuit temp drops to 97.3 °F**

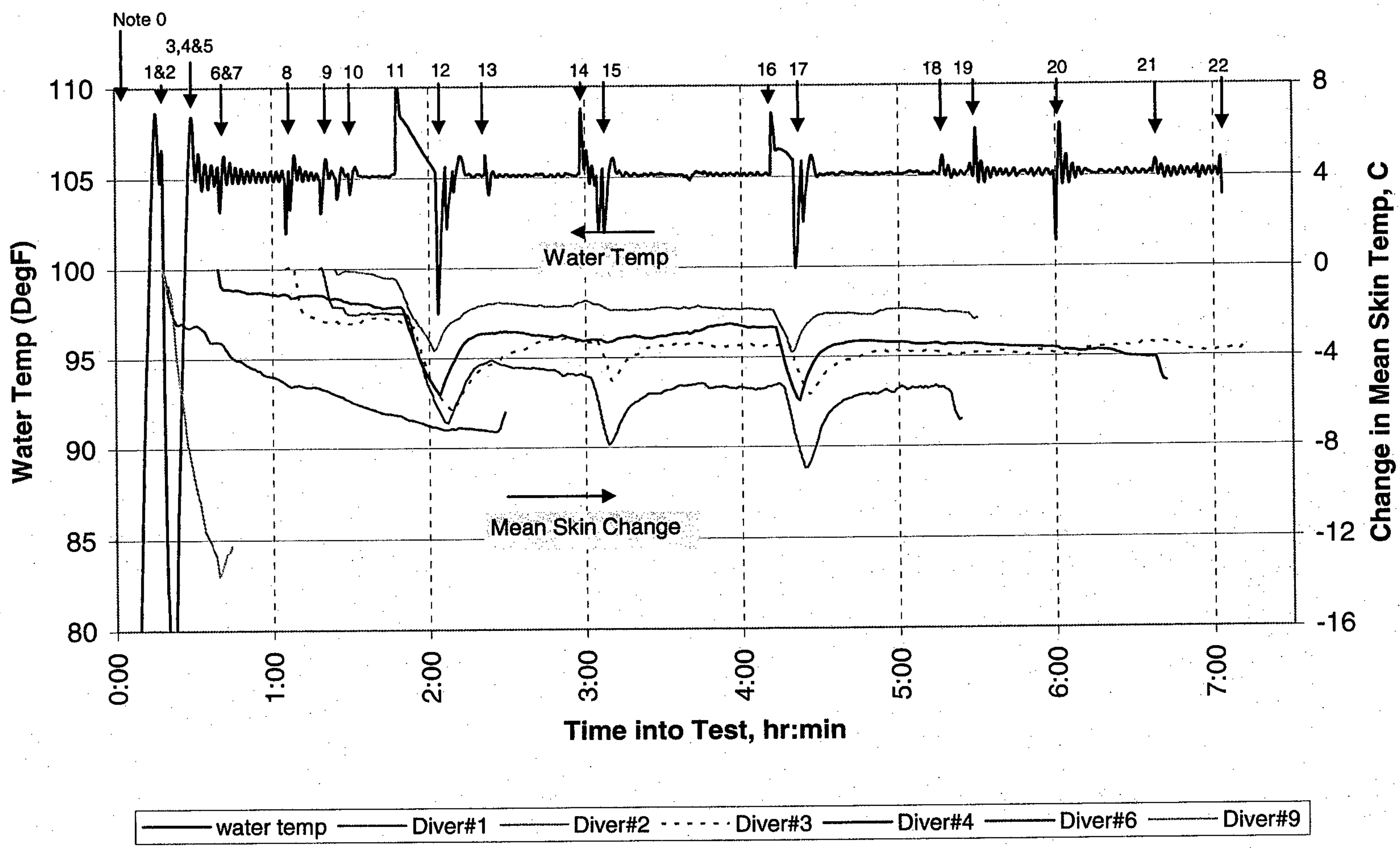
1016	2:06	Circuit temp back up to 105 °F; switched to 2 pumps
1019	2:09	Switched to 3 pumps
1030	2:20	Switched to 2 pumps
1031	**2:21**	**13—Diver #6 aborts due to finger temp; confirmed kink in tube suit; 4 divers on circuit**
1107	2:57	Switched to 1 pump prior to locking out 2 divers
1108	**2:58**	**14—Divers #1 and #3 disconnect from circuit. 2 divers on circuit; circuit temp rise to 108.6 °F**
1111	3:01	Circuit temp back down to 105 °F
1114	**3:04**	**15—Diver2 #1 and #3 reconnect into hot water circuit; 4 divers on circuit; circuit temp drops to 102 °F**
1116	3:06	Circuit temp returns to 105 °F; switch to 2 pumps
1221	4:11	Switch to 1 pump prior to locking out 4 divers
1222	**4:12**	**16—4 remaining divers disconnect from circuit; 0 divers on circuit; circuit temp rise to 108.5 °F**
1229	4:19	Circuit temp back down to 105.2 °F
1230	**4:20**	**17—Divers #1, #2, #3, and #4 reconnect to circuit; circuit temp drops to 100.4 °F; 4 divers on circuit**
1232	4:22	Circuit temp back down to 105.0 °F, switch to 2 pumps
1326	**5:16**	**18—Diver #1 voluntarily aborts due to toe temp (possible leak in suit); 3 divers on circuit**
1336	**5:26**	**19—Diver #2 aborted due to toe temp; 2 divers on**
1337	5:27	Switched to 1 pump
1409	**5:59**	**20—Changed H_2 cylinders (out cylinder had dropped to 350 psi)**
1446	**6:36**	**21—Diver #4 completes 6 hr dive and disconnects from circuit; 1 diver left on circuit**
1512	**7:02**	**22—Diver #3 completes 6 hr dive and disconnects from circuit; test terminated**



Day #4: Heater response to variable diver loading.

Notes:

0—Start heater and start logs (H_2 bottle press = 2100psi)
1—Divers #6 and #9 plugged into hot water circuit; circuit temp drops to 70 °F due to apparent circuit leak
2—Diver #6 disconnects and returns to surface to adjust hood
3—Diver #6 reconnects
4—Diver #9 disconnects and returns to surface to replace finger sensor
5—Diver #9 reconnected to circuit; 2 divers on circuit
6—Diver #4 plugged into circuit; 3 divers on
7—Diver #9 aborts due to flooded suit and cold feet; 2 divers on circuit
8—Diver #3 plugged into hot water circuit; 3 divers on circuit; switched to 2 pumps
9—Diver #1 plugged into hot water circuit; 4 divers on
10—Diver #2 plugged into hot water circuit; 5 divers on circuit; switched to 3 pumps
11—Divers #1, #2, #3, and #4 disconnect from hot water circuit; 1 diver on circuit; circuit temp rises to 108 °F
12—Divers #1, #2, #3, and #4 reconnect to circuit; 5 divers on; circuit temp drops to 97.3 °F
13—Diver #6 aborts due to finger temp; confirmed kink in tube suit; 4 divers on circuit
14—Divers #1 and #3 disconnect from circuit. 2 divers on circuit; circuit temp rises to 108.6 °F
15—Divers #1 and #3 reconnect into hot water circuit; 4 divers on circuit; circuit temp drops to 102 °F
16—4 remaining divers disconnect from circuit; 0 divers on circuit; circuit temp rises to 108.5 °F
17—Divers #1, #2, #3, and #4 reconnect to circuit; circuit temp drops to 100.4 °F; 4 divers on circuit
18—Diver #1 voluntarily aborts due to toe temp (possible leak in suit); 3 divers on circuit
19—Diver #2 aborted due to toe temp; 2 divers on
20—Changed H_2 cylinders (out cylinder had dropped to 350 psi)
21—Diver #4 completes 6 hr dive and disconnects from circuit; 1 diver left on circuit
22—Diver #3 completes 6 hr dive and disconnects from circuit; test terminated



Day #4: Effect of water circuit temperatures on mean skin temperatures.

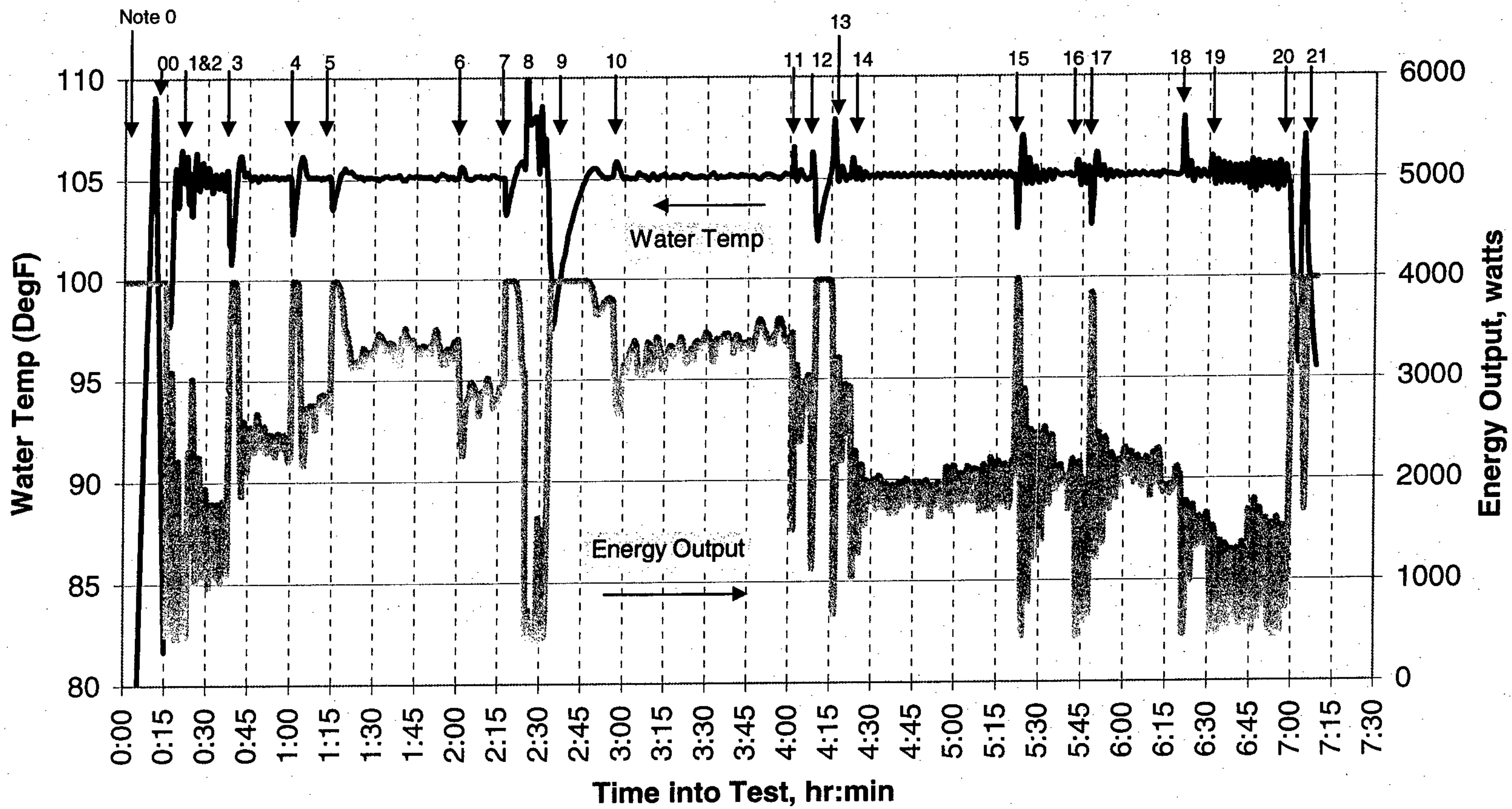
Running Narrative of NEDU Heater Testing

Day 5 – 18 Feb 2005

Water Temp: 38 °F
H_2 Supply Pressure: 180 psi
Air Supply Pressure: 250 psi

Computer Time	Time Into Test, hr:min	Event
0746	**0:00**	**0—Start heater and start logs (H_2 bottle press = 2000 psi); 20.9% O_2 exit**
0747	0:01	19.7% O_2 exit
0750	0:04	16.9% O_2
0752	0:06	10.7% O_2; hydrogen supply automatically turns off:
0804	**0:18**	**00—Rebooted computer (12.3% O_2 exit; H_2 bottle press = 1950 psi)**
0809	**0:23**	**1—Diver #2 plugged into hot water circuit;** 13.9% O_2 exit
0810	**0:24**	**2—Diver #1 plugged into hot water circuit;** 13.2% O_2 exit
0824	**0:38**	**3—Divers #3 and #4 plugged into hot water circuit; 4 divers on circuit;** 10.5% O_2 exit; H_2 bottle press = 1825 psi
0833	0:47	4 divers on; 9.1% O_2 exit; H_2 bottle press = 1800 psi
0846	**1:00**	**4—Diver #6 plugged into hot water circuit; 5 divers on**
0852	1:06	5 divers on circuit; 7.2% O_2 (H_2 bottle press = 1700 psi)
0901	**1:15**	**5—Diver #8 plugged into hot water circuit; 6 divers on circuit;** 7.4% O_2 (H_2 bottle press = 1625 psi)
0908	1:22	6 divers on circuit; 5.2% O_2 (H_2 bottle press = 1575 psi)
0928	1:42	6 divers on circuit; 5.6% O_2 (H_2 bottle press = 1425 psi)
0938	1:52	6 divers on circuit; 5.5% O_2 (H_2 bottle press = 1400 psi)
0946	**2:00**	**6—Diver #3 disconnected from hot water circuit and surfaced to adjust discomfort in suit; 5 divers on**
0953	2:07	Diver #4 reported left arm wet
1003	**2:17**	**7—Diver #3 reenters water and reconnects to circuit; 6 divers on circuit; 7.3% O_2 (H_2 bottle press = 1210 psi)**
1013	**2:27**	**8—All 6 divers unplug from hot water circuit**
1018	**2:32**	**9—All 6 divers reconnect to circuit**
1025	2:39	6 divers on circuit; 5.9% O_2 (H_2 bottle press = 1110 psi)
1027	2:41	6 divers on circuit; 4.5% O_2 (H_2 bottle press = 1100 psi)
1030	2:44	6 divers on circuit; 3.8% O_2 (H_2 bottle press = 1100 psi)
1032	2:46	6 divers on circuit; 3.2% O_2
1036	2:50	6 divers on circuit; 3.0% O_2
1042	**2:56**	**10—Diver #4 aborted due to finger temp; left arm flooded; 5 divers on circuit;** 3.7% O_2 (H_2 bottle press = 1000 psi)
1049	3:03	5 divers on circuit; 5.6% O_2 (H_2 bottle press = 950 psi)

1145	3:59	5 divers on circuit; 5.3% O_2; 3 pumps
1147	**4:01**	**11—Diver #3 unplugged from circuit to adjust communications problem; 4 divers on circuit**
1155	**4:09**	**12—Diver #3 reconnects; 5 divers on circuit; water temp fell to 101.7 °F**
1201	**4:15**	**13—Diver #8 voluntarily aborted due to tight neck seal causing discomfort; 4 divers on circuit;** 4.3% O_2 (H_2 bottle press = 500 psi)
1207	4:21	7.5% O_2; 4 divers on circuit
1208	**4:22**	**14—Diver #1 voluntarily aborted due to cold; lower suit was flooded; 3 divers on circuit;** 7.7% O_2 exit
1224	4:38	11.4% O_2 (H_2 bottle press = 400 psi); 3 divers on
1240	4:54	11.6% O_2 (H_2 bottle press = 320 psi); 3 divers on
1306	**5:20**	**15—Changed hydrogen supply cylinder**
1327	5:41	10.9% O_2; 3 divers on
1329	**5:43**	**16—Diver #3 disconnects from circuit to move past untangle umbilicals; 2 divers on circuit**
1334	**5:48**	**17—Divers #3 reconnects to circuit; 3 divers on circuit**
1341	5:55	11.1% O_2; 3 divers on
1351	6:05	10.8% O_2; 3 divers on
1404	6:18	11.1% O_2; 3 divers on
1406	**6:20**	**18—Diver #2 completes 6 hr dive and disconnects; 2 divers on circuit**
1419	**6:33**	**19—Diver #3 completes 6 hr dive and disconnects; 1 diver left on circuit; 14.1% O_2**
1424	6:38	14.9% O_2; 1 diver
1428	6:42	15.2% O_2; 1 diver
1444	6:58	15.3% O_2; 1 diver
1445	**6:59**	**20—Diver #6 completes 6 hr dive and prepares to disconnect; heater hydrogen shut off**
1451	**7:05**	**21—Diver #6 disconnects and surfaces; heater had been restarted due to delay in Diver #6 surfacing; dive terminated**



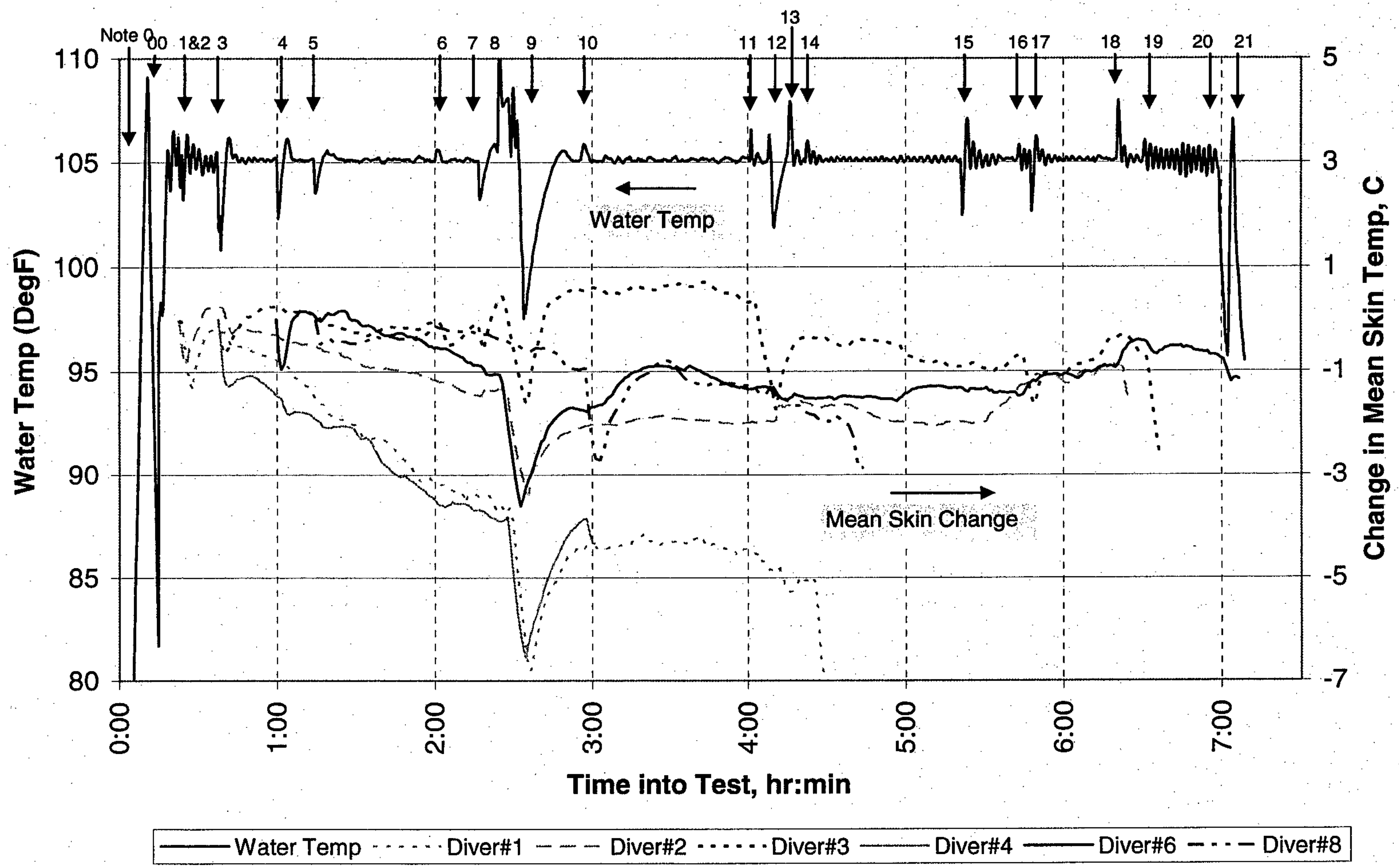
Day #5: Heater response to variable diver loading.

Notes:

0—Start heater and start logs (H_2 bottle press = 2000 psi); 20.9% O_2 exit
1—Diver #2 plugged into hot water circuit; 13.9% O_2 exit
2—Diver #1 plugged into hot water circuit; 13.2% O_2 exit

3—Divers #3 and #4 plugged into hot water circuit; 4 divers on circuit; 10.5% O_2 exit; H_2 bottle press = 1825 psi
4—Diver #6 plugged into hot water circuit; 5 divers on
5—Diver #8 plugged into hot water circuit; 6 divers on circuit; 7.4% O_2 (H_2 bottle press = 1625 psi)
6—Diver #3 disconnected from hot water circuit and surfaced to adjust discomfort in suit; 5 divers on
7—Diver #3 reenters water and reconnects to circuit; 6 divers on circuit; 7.3% O_2 (H_2 bottle press = 1210 psi)
8—All 6 divers unplug from hot water circuit
9—All 6 divers reconnect to circuit
10—Diver #4 aborted due to finger temp; left arm flooded; 5 divers on circuit; 3.7% O_2 (H_2 bottle press = 1000 psi)

11—Diver #3 unplugged from circuit to adjust communications problem; 4 divers on circuit
12—Diver #3 reconnects; 5 divers on circuit; water temp fell to 101.7 °F
13—Diver #8 voluntarily aborted due to tight neck seal causing discomfort; 4 divers on circuit; 4.3% O_2 (H_2 bottle press = 500 psi)
14—Diver #1 voluntarily aborted due to cold; lower suit was flooded; 3 divers on circuit; 7.7% O_2 exit
15—Changed hydrogen supply cylinder
16—Diver #3 disconnects from circuit to move past untangle umbilicals; 2 divers on circuit
17—Divers #3 reconnects to circuit; 3 divers on circuit
18—Diver #2 completes 6 hr dive and disconnects; 2 divers on circuit
19—Diver #3 completes 6 hr dive and disconnects; 1 diver left on circuit; 14.1% O_2
20—Diver #6 completes 6 hr dive and prepares to disconnect; heater hydrogen shut off
21—Diver #6 disconnects and surfaces; heater had been restarted due to delay in Diver #6 surfacing; dive terminated



Day #5: Effect of water circuit temperatures on mean skin temperatures.